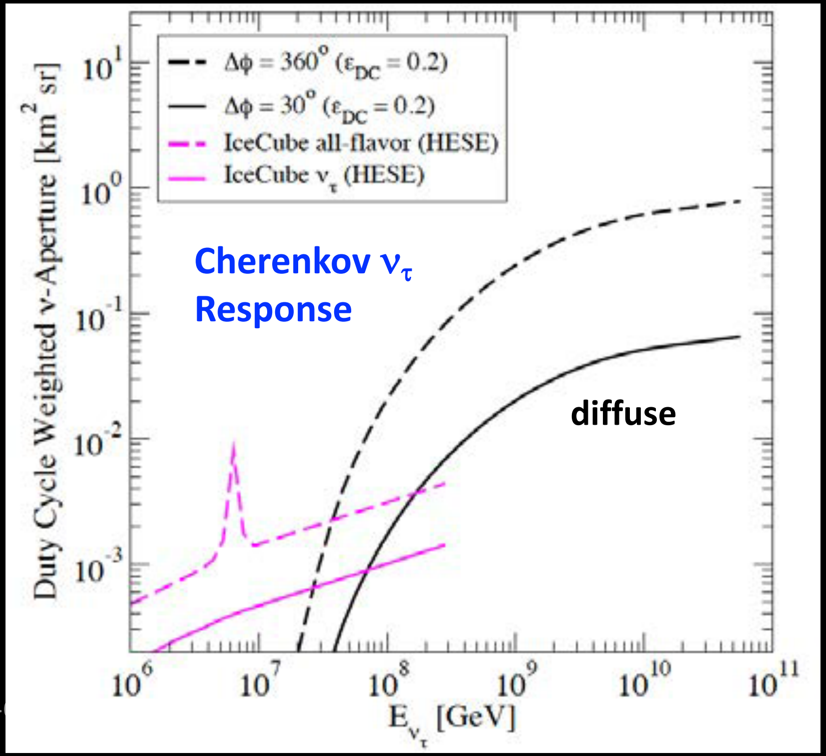
POEMMA: Probe Of Extreme Multi-Messenger Astrophysics

A NASA Probe-class mission to perform transformational measurements of UHECRs and Cosmic Neutrinos.

John Krizmanic

CRESST/NASA/GSFC/UMBC

for the POEMMA Collaboration



POEMMA Study Collaboration

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NASA/MSFC: Mark J. Christl (study deputy PI), Roy M. Young, Peter Bertone

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City University of New York, Lehman College: Luis Anchordoqu, Thomas C. Paul, Jorge. F. Soriano

Georgia Institute of Technology: A. Nepomuk Otte

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Gran Sasso Science Institute: Roberto Aloisio, A. L. Cummings, I. De Mitri; INFN Frascati: Marco Ricci

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SWITZERLAND: University of Geneva: Andrii Neronov

SLOVAKIA: IEP, Slovak Academy of Science: Simon Mackovjak

JAPAN: RIKEN: Marco Casolino

GERMANY: KIT: Michael Unger; ESO: F. Oikonomou

40+ scientists from 21+ institutions (US + 6)

OWL, JEM-EUSO, Auger, TA, Veritas, CTA, Fermi, Theory

POEMMA: Science Goals

POEMMA Science goals:

primary

- **Discover the origin of Ultra-High Energy Cosmic Rays**

  Measure Spectrum, composition, Sky Distribution at Highest Energies (E_{CR} > 20 EeV)

  Requires very good angular, energy, and X_{max} resolutions: stereo fluorescence

  High sensitivity UHE neutrino measurements via stereo fluorescence measurements

- **Observe Neutrinos from Transient Astrophysical Events**

  Measure beamed Cherenkov light from upward-moving EAS from τ-leptons source by ν_τ interactions in the Earth (E_ν > 20 PeV)

  Requires tilted-mode of operation to view limb of the Earth & ~10 ns timing

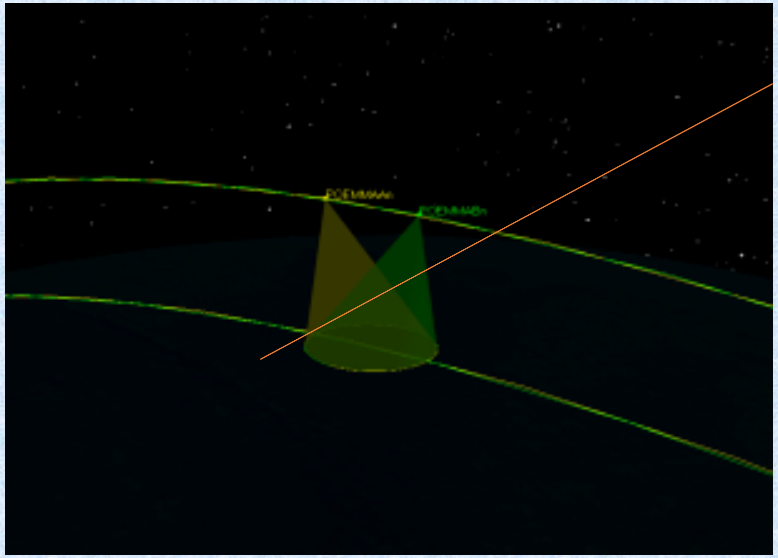
  Allows for tilted UHECR air fluorescence operation, higher GF but degraded resolutions

secondary

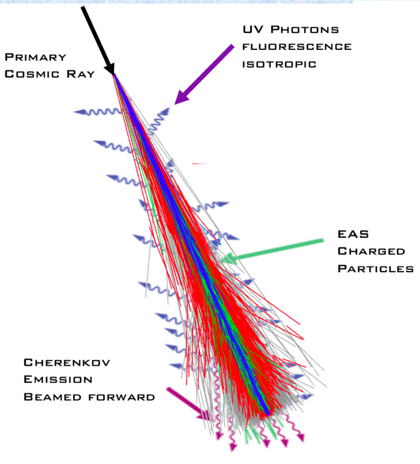
$\sqrt{s} \approx 450$ TeV @ 100 EeV

- study fundamental physics with the most energetic cosmic particles: CRs and Neutrinos
- search for super-Heavy Dark Matter
- study Atmospheric Transient Events, survey Meteor Population

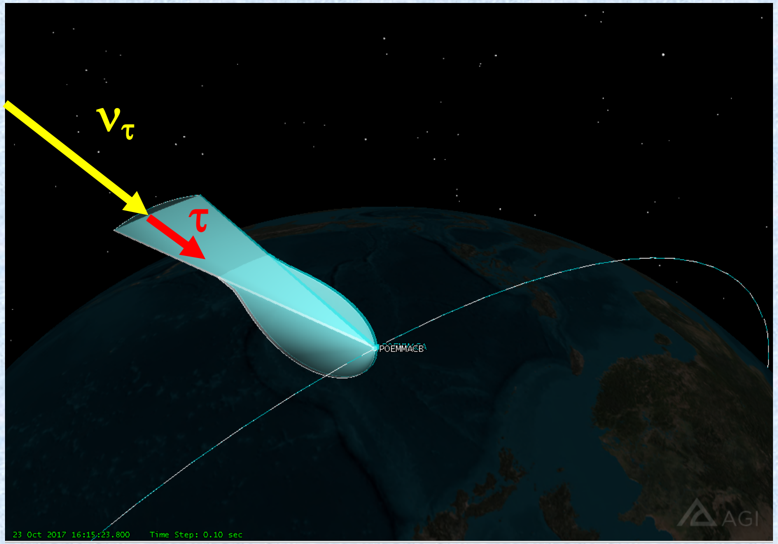
POEMMA Operational Modes: UHECR Stereo versus Limb-viewing Neutrino



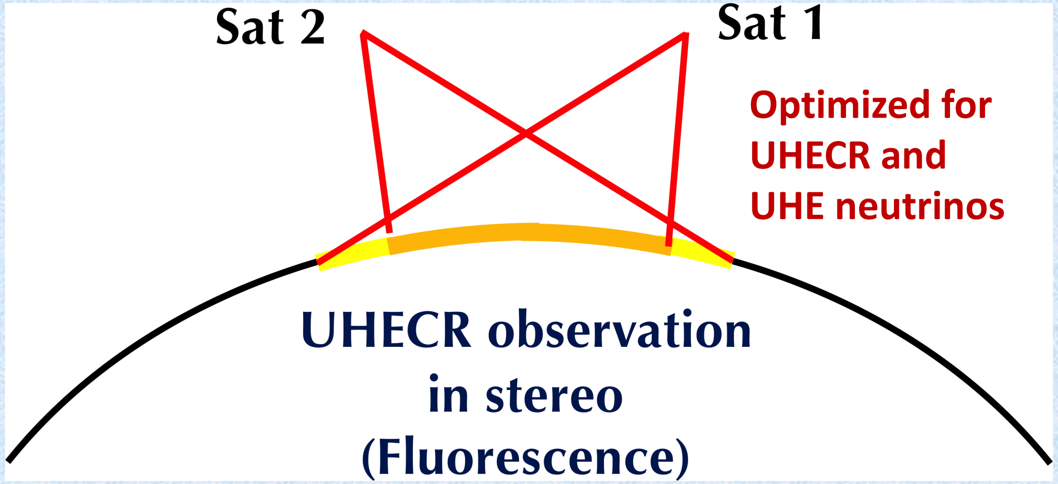
Stereo Viewing of UHECRs E ≳ 20 EeV
via Fluoresence: 10's of μsec timescale

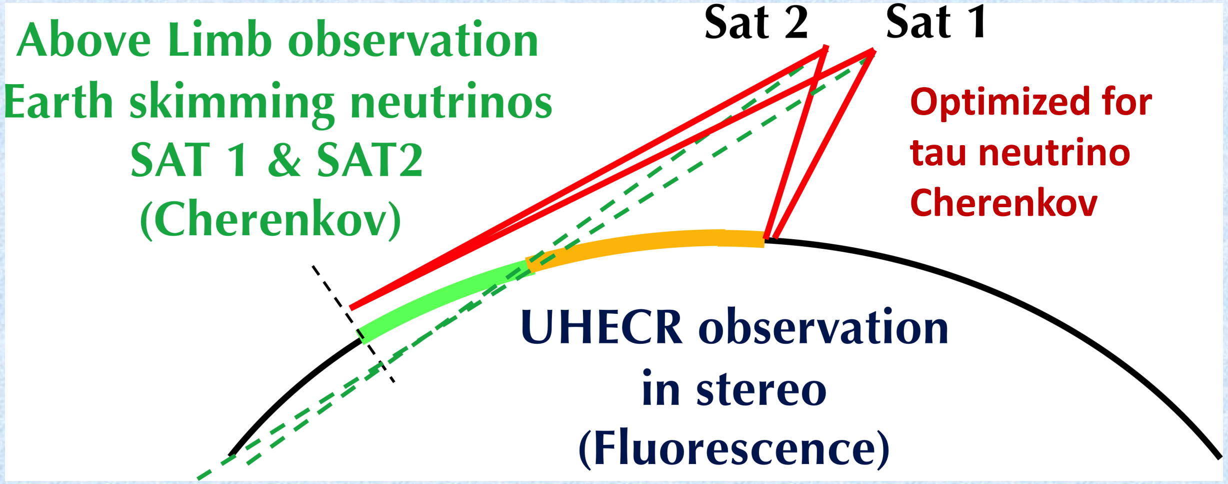


Dark, quasi-moon less nights:
Fluorescence Duty Cycle: 11%
Cherenkov Duty Cycle: 20%

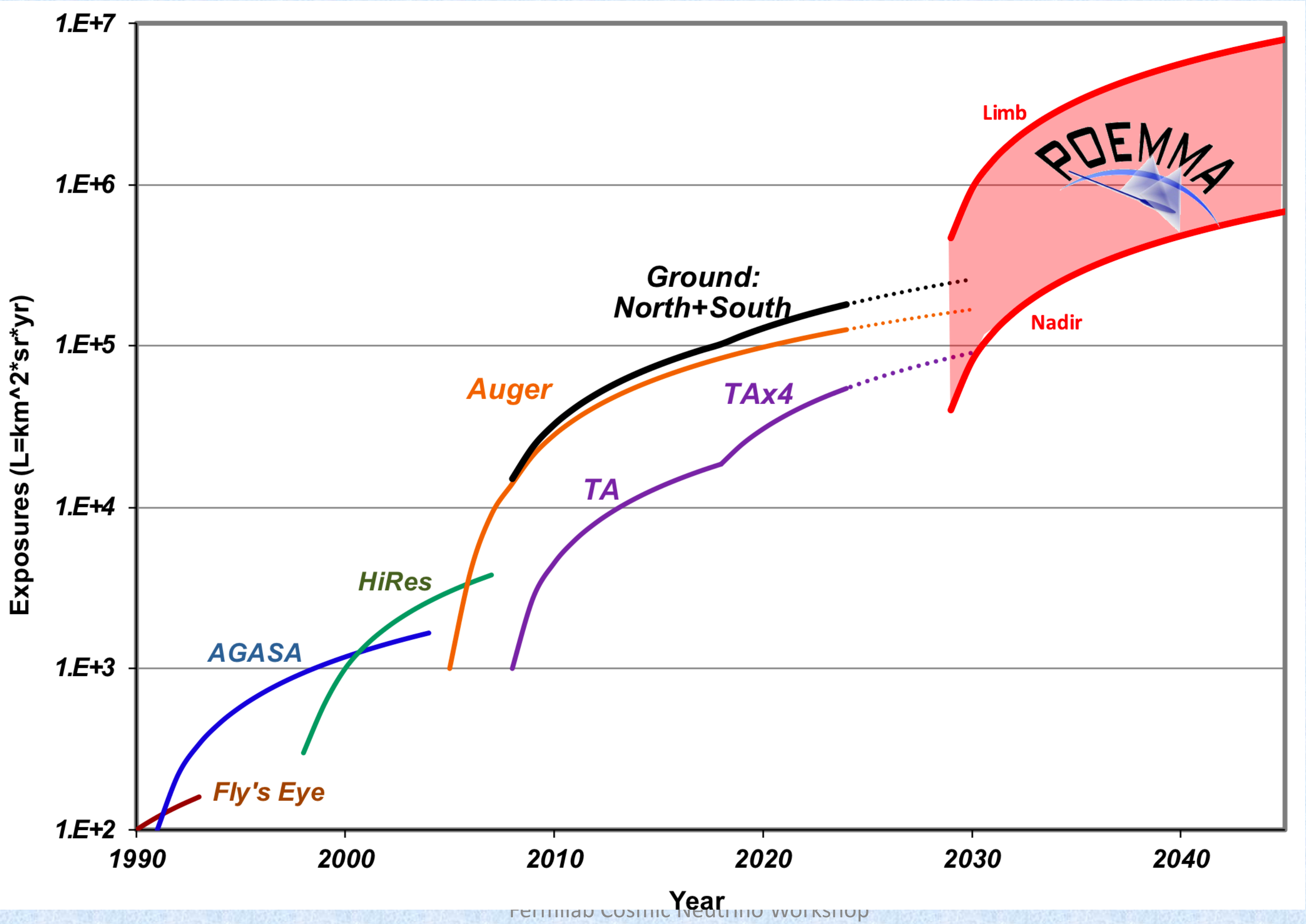


Upward τ-lepton EAS E ≳ 20 PeV
via Cherenkov: ~10 nsec timescale

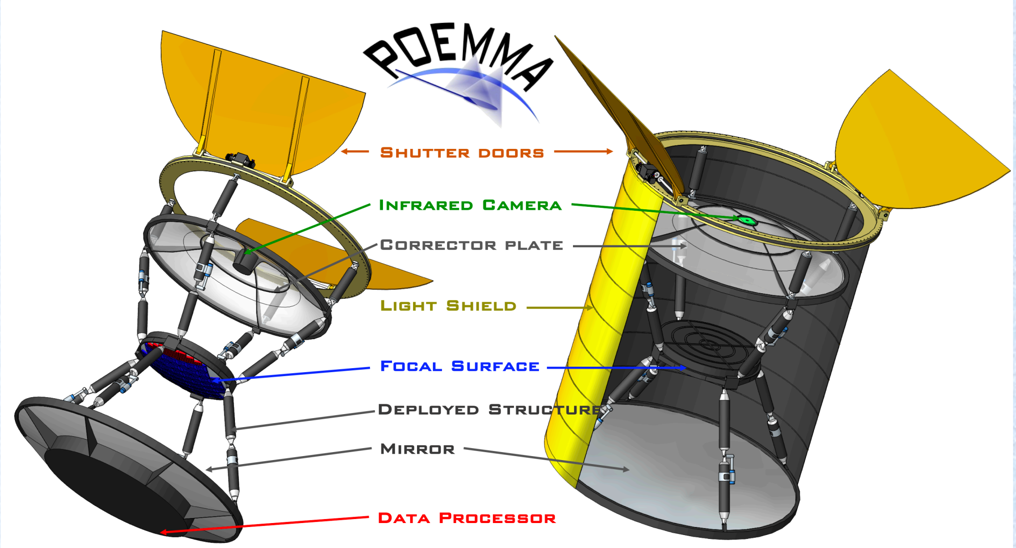


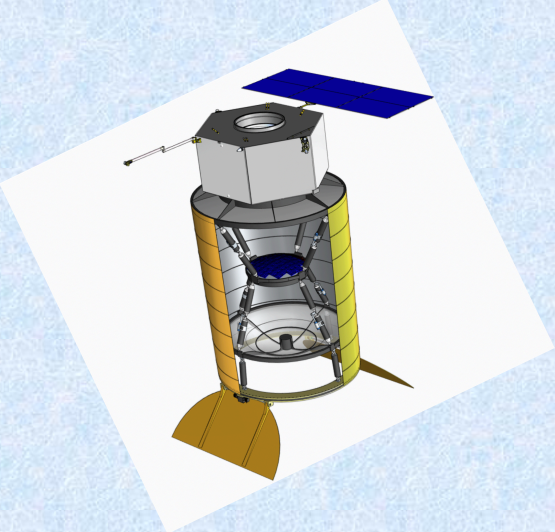


POEMMA: UHECR Exposure History



POEMMA: Instruments defined by weeklong IDL run at GSFC





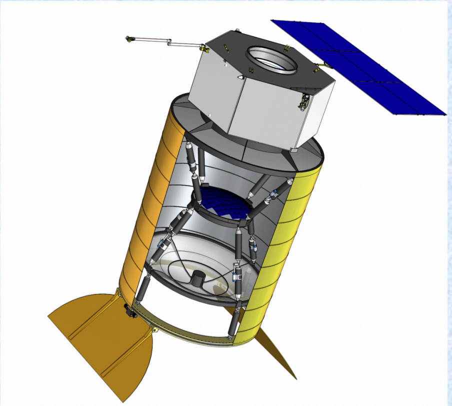
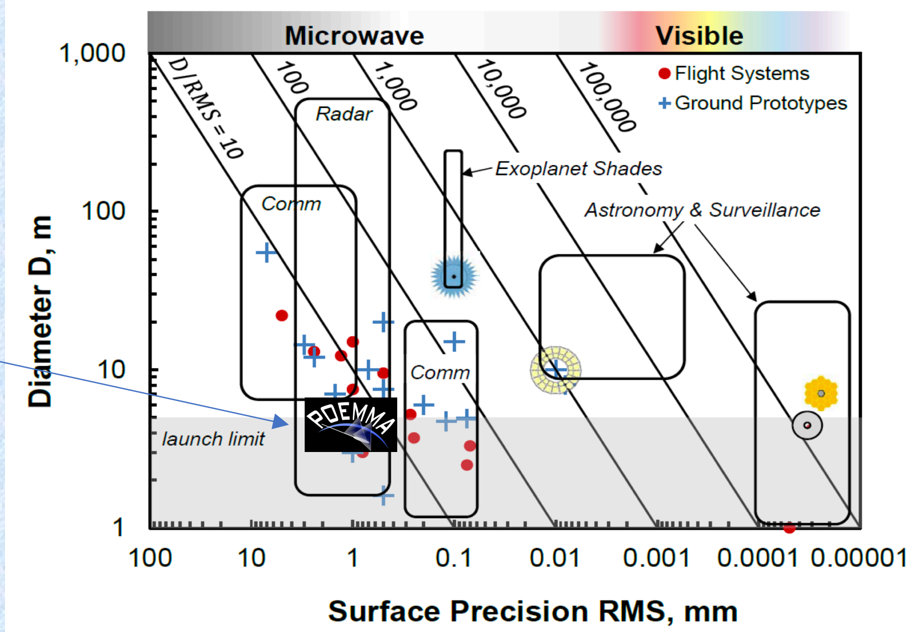


TABLE I: POEMMA Specifications:

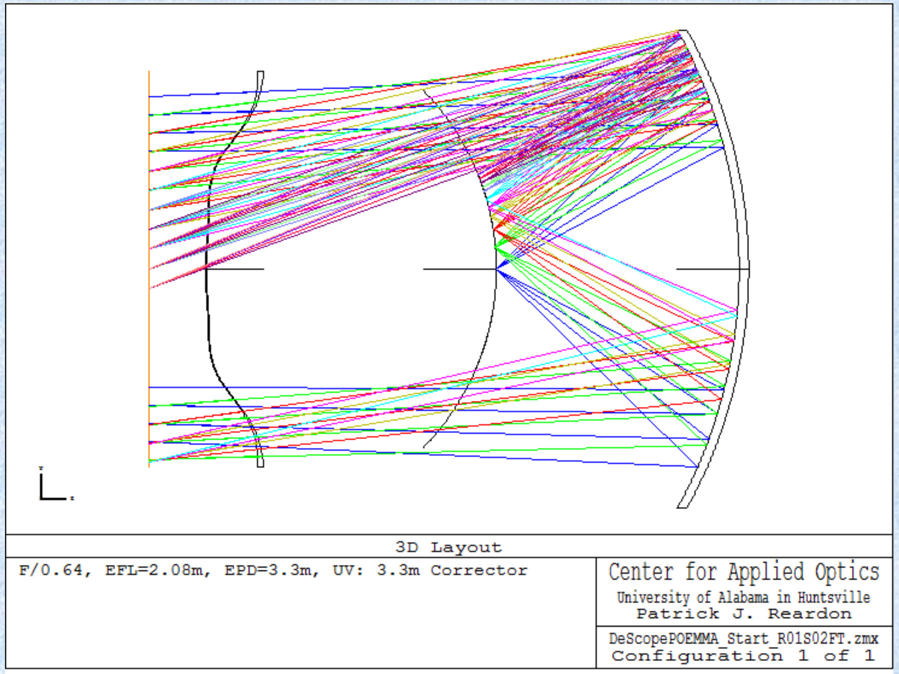
Photometer	Components		Spacecraft	
Optics	Schmidt	45° full FoV	Slew rate	90° in 8 min
	Primary Mirror	4 m diam.	Pointing Res.	0.1°
	Corrector Lens	3.3 m diam.	Pointing Know.	0.01°
	Focal Surface	1.6 m diam.	Clock synch.	10 nsec
	Pixel Size	3×3 mm^2	Data Storage	7 days
	Pixel FoV	0.084°	Communication	S-band
PFC	MAPMT (1μs)	126,720 pixels	Wet Mass	3,450 kg
PCC	SiPM (20 ns)	15,360 pixels	Power (w/cont)	550 W
Photometer	(One)		Mission	(2 Observatories)
	Mass	1,550 kg	Lifetime	3 year (5 year goal)
	Power (w/cont)	700 W	Orbit	525 km, 28.5° Inc
	Data	< 1 GB/day	Orbit Period	95 min
			Observatory Sep.	~25 - 1000+ km

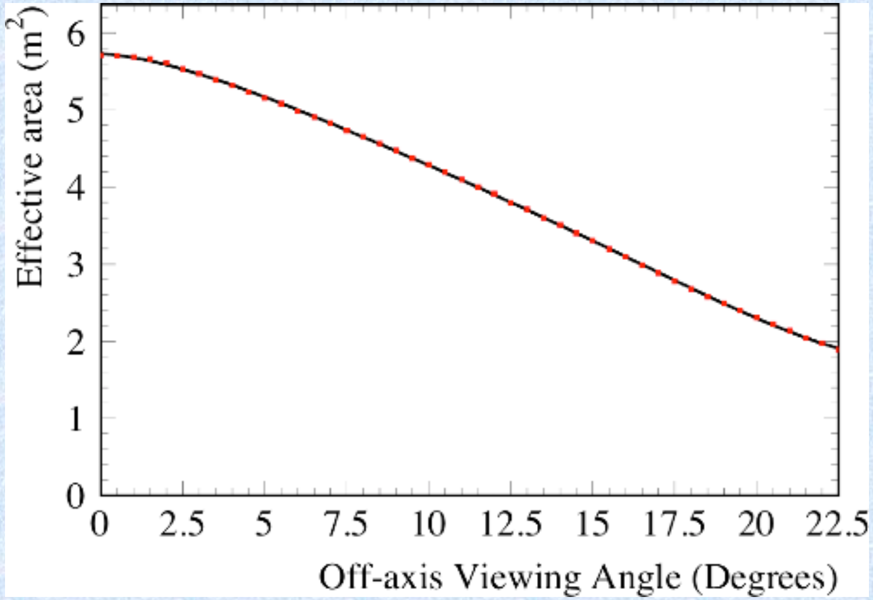
Each Observatory = Photometer + Spacecraft; POEMMA Mission = 2 Observatories



Imaging ~10^4 away from diffraction limit

POEMMA: Schmidt Telescope details





Two 4 meter F/0.64 Schmidt telescopes: 45° FoV

Primary Mirror: 4 meter diameter

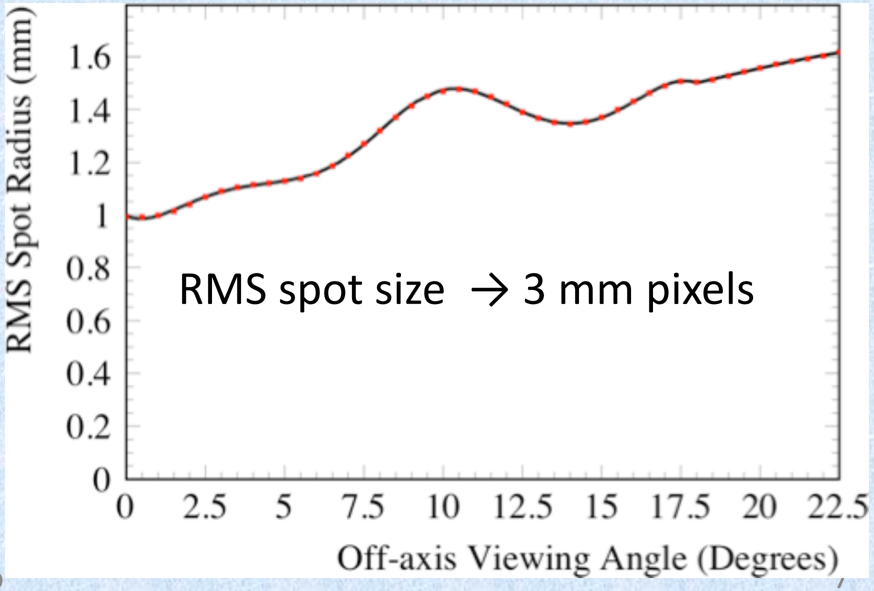
Corrector Lens: 3.3 meter diameter

Focal Surface: 1.6 meter diameter

Optical Area$_{EFF}$: ~6 to 2 m^2

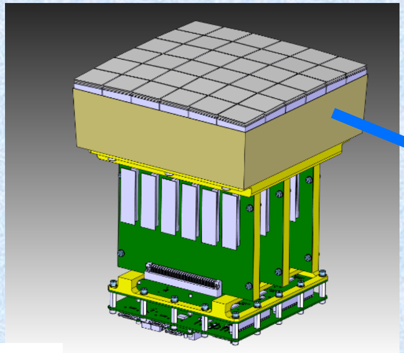
Hybrid focal surface (MAPMTs and SiPM)

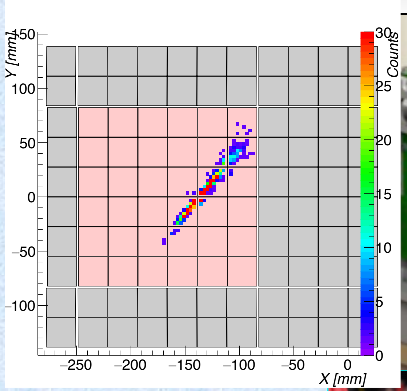
3 mm linear pixel size: 0.084° FoV

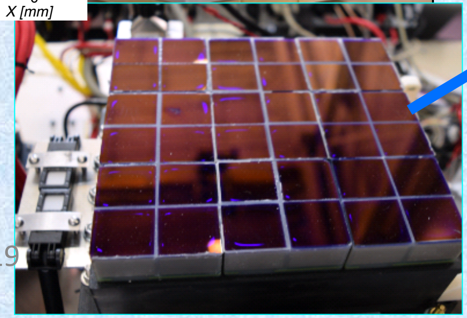


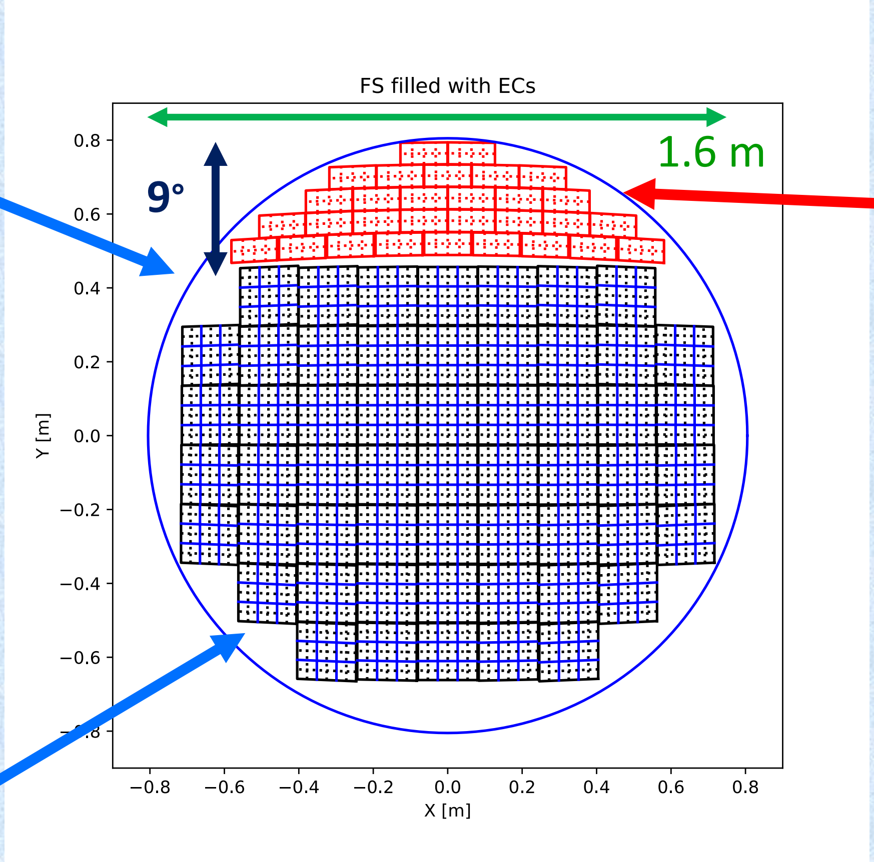
POEMMA: Hybrid Focal Plane

UV Fluorescence Detection using MAPMTs with BG3 filter (300 – 500 nm) developed by JEM-EUSO: 1 usec sampling





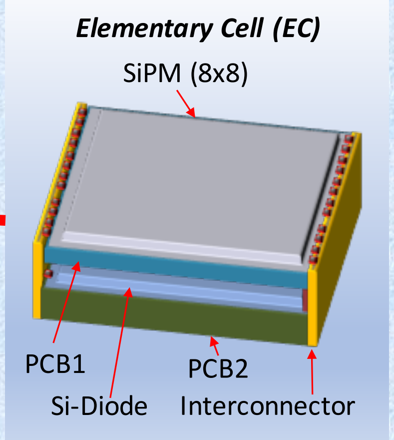




55 Photo Detector Modules (PDMs)= 126,720 pixels

1 PDM = 36 MAPMTs = 2,304 pixels

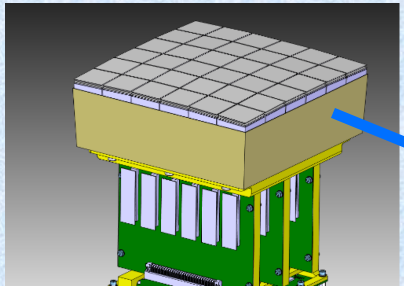
Cherenkov Detection with SiPMs (300 – 1000 nm): 20 nsec sampling

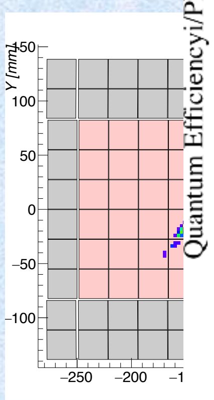


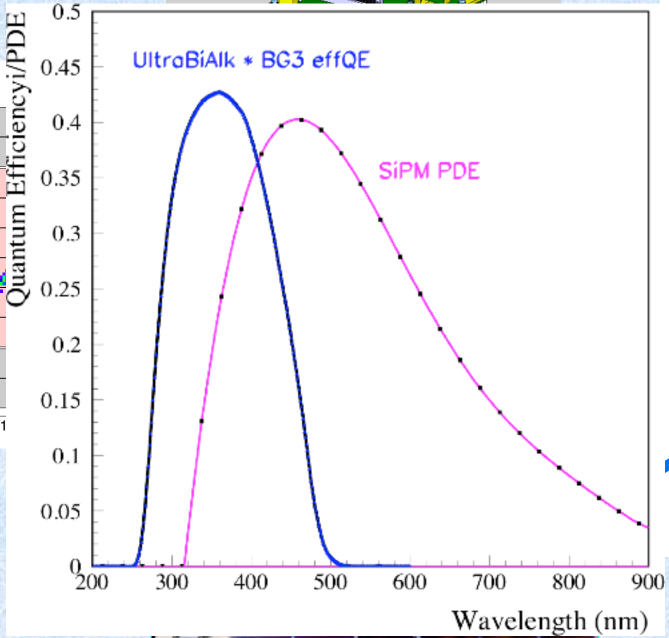
30 SiPM focal surface units
Total 15,360 pixels
512 pixels per FSU (64x4x2)
Si-Diode for LEO radiation backgrounds rejection

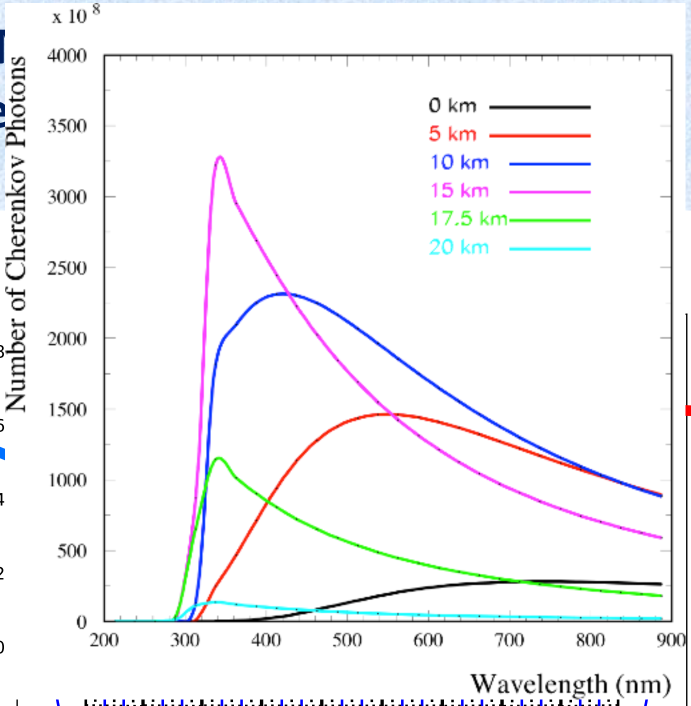
POEMMA: Hybrid Focal Plane

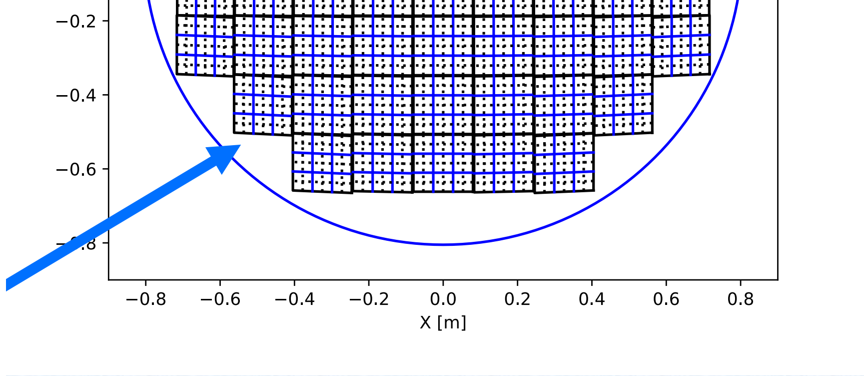
UV Fluorescence Detection using MAPMTs with BG3 filter (300 – 500 nm) developed by JEM-EUSO: 1 usec sampling



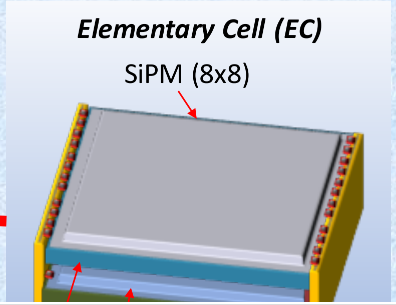


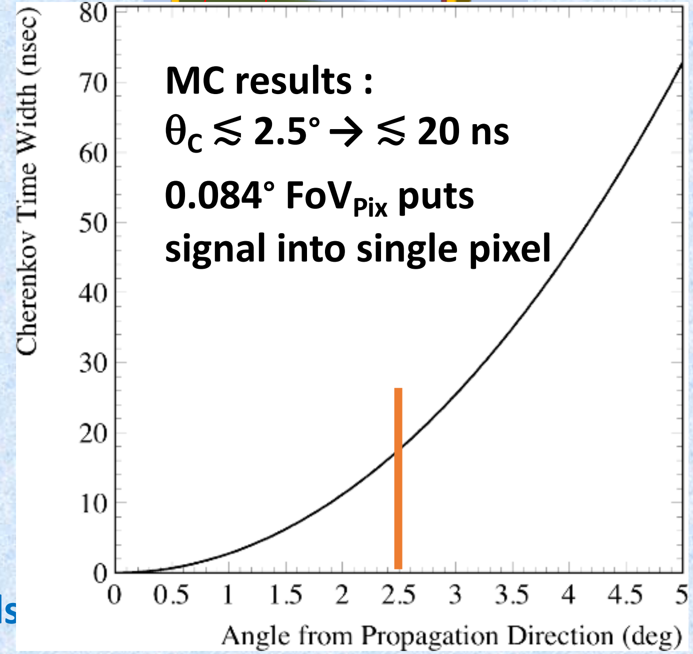






Cherenkov Detection with SiPMs (300 – 1000 nm): 20 nsec sampling





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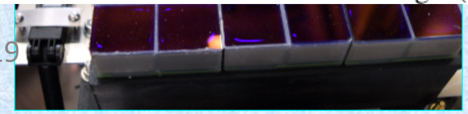
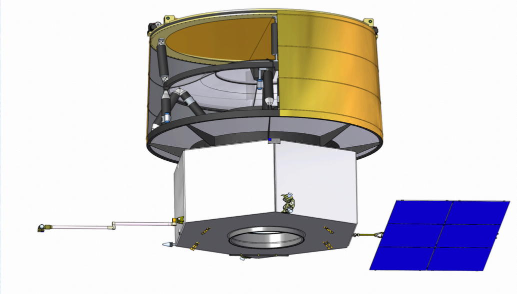
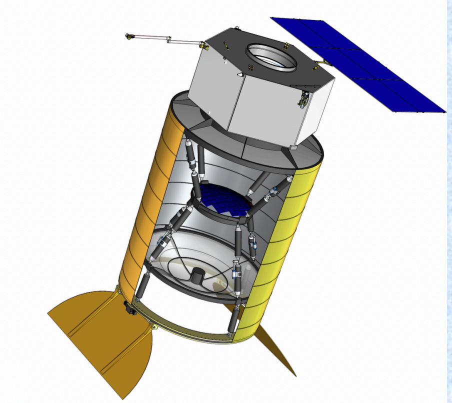


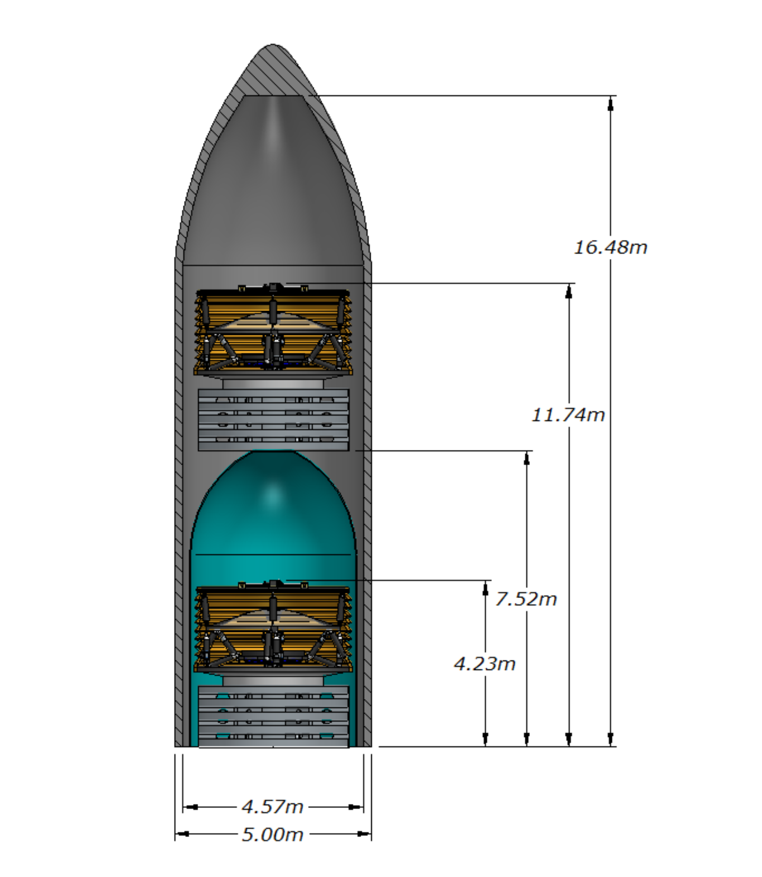
POEMMA: Mission (Class B) defined by weeklong MDL run at GSFC

Mission Lifetime:	3 years (5 year goal)
Orbits:	525 km, 28.5° Inc
Orbit Period:	95 min
Satellite Separation:	~25 km – 1000+ km
Satellite Position:	1 m (knowledge)
Pointing Resolution:	0.1°
Pointing Knowledge:	0.01°
Slew Rate:	8 min for 90 °
Satellite Wet Mass:	3860 kg
Power:	1250 W (w/contig)
Data:	< 1 GB/day
Data Storage:	7 days
Communication:	S-band
Clock synch (timing):	10 nsec

Flight Dynamics/Propulsion:
- 300 km ⟹ 50 km SatSep
  - Puts both in CherLight Pool
- Δt =3 hr, 9 times
- Δt 24 hr, 90 times







Dual Manifest Atlas V

Operations:
- Each satellite collects data autonomously
- Coincidences analyzed on the ground
- View the Earth at near-moonless nights, charge in day and telemeter data to ground
- ToO Mode: dedicated com uplink to re-orient satellites if desired

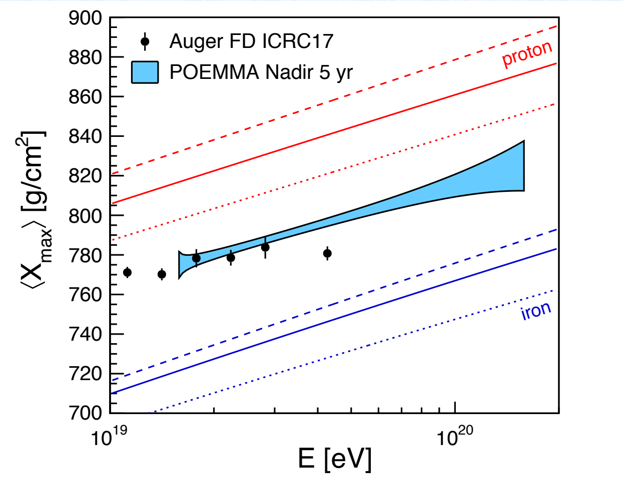
POEMMA: UHECR Performance: *see arXive:1907.03694*

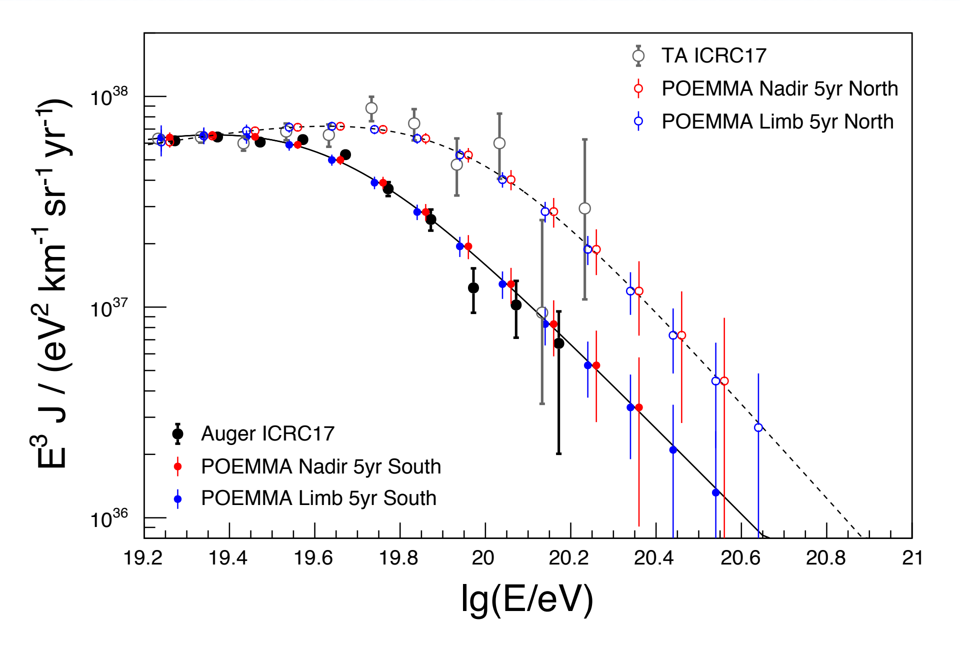
Significant increase in exposure with all-sky coverage

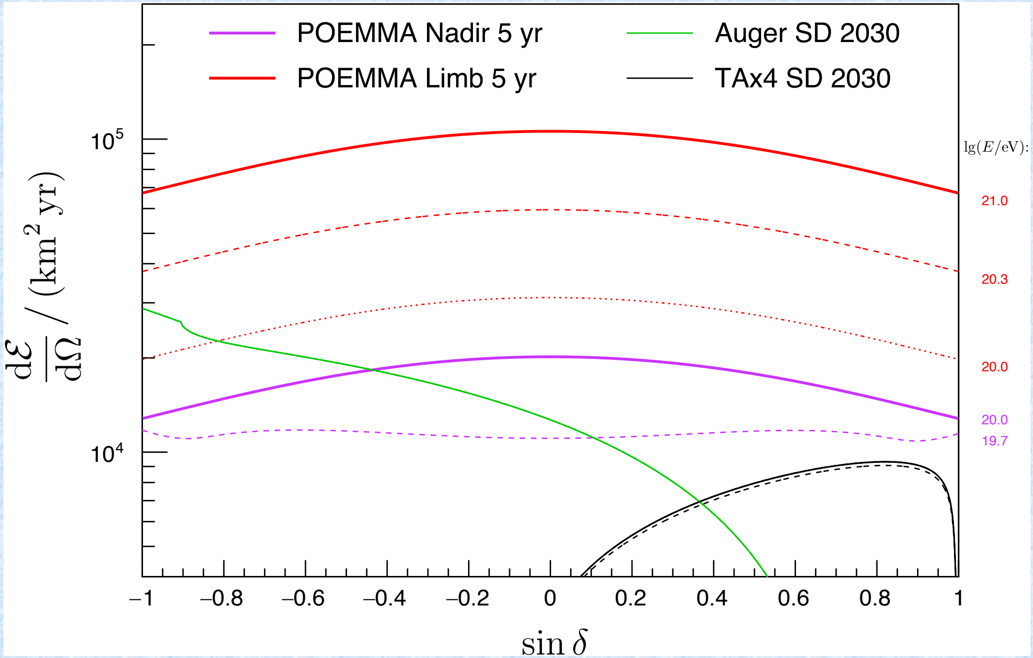
Uniform sky coverage to **guarantee the discovery of UHECR sources**

Spectrum, Composition, Anisotropy $E_{CR} \geq 50$ EeV

Very good energy (< 20%), angular ($\lesssim 1.2°$), and composition ($\sigma_{Xmax} \lesssim 30$ g/cm²) resolutions

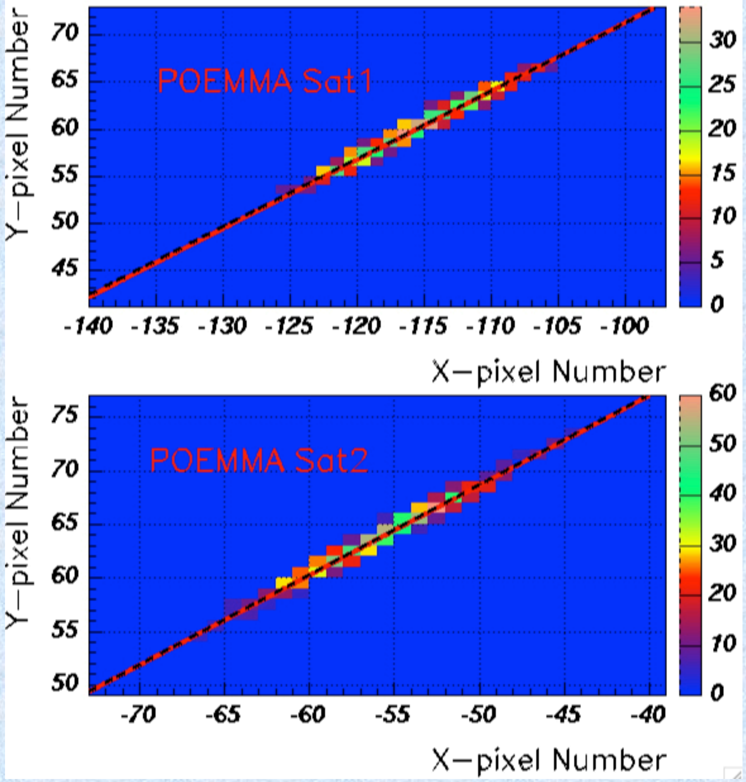




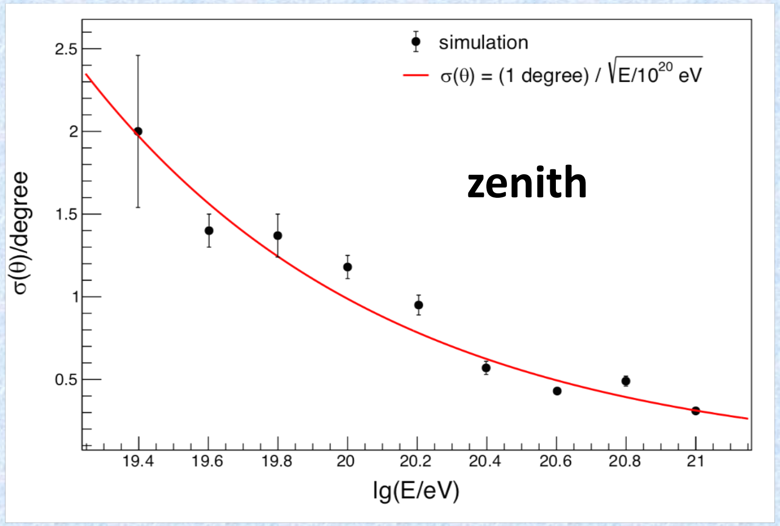


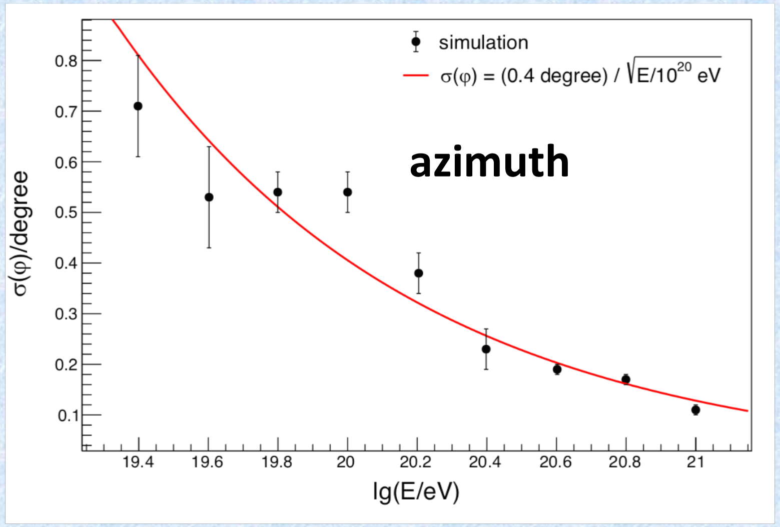
POEMMA: stereo reconstructed angular resolution

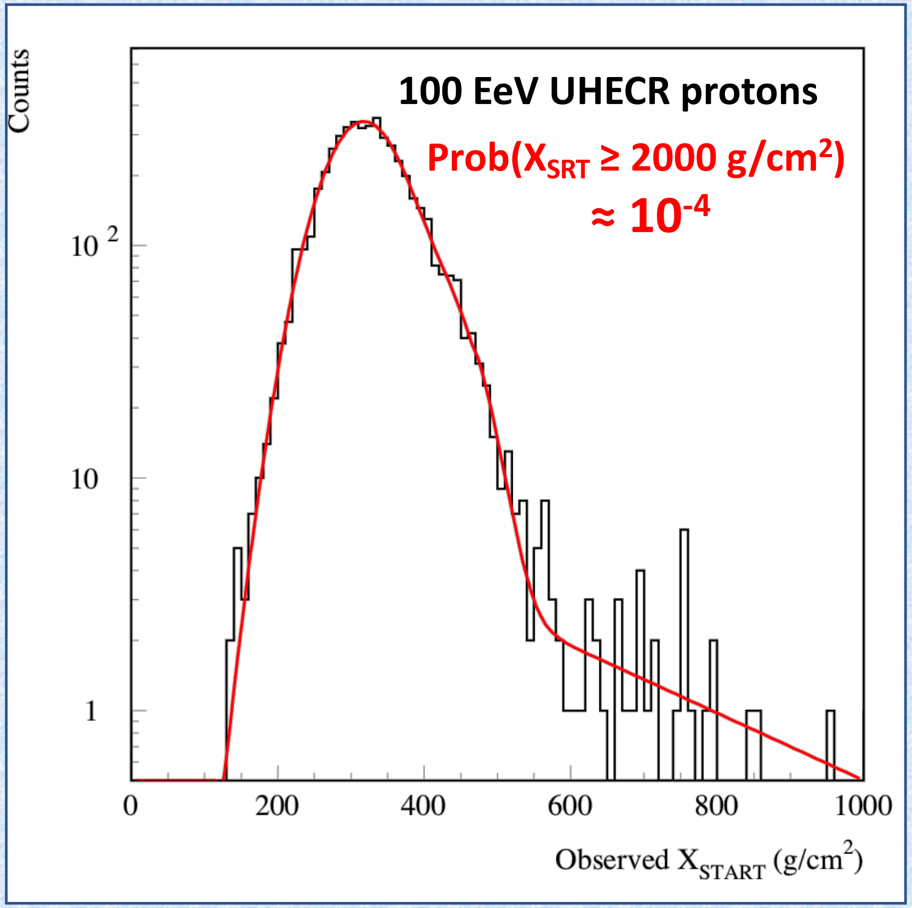
Excellent angular resolution → accurate determination of slant depth of EAS starting point



50 EeV simulated event







UHECR 100% proton assumption most conservative

POEMMA: Air fluorescence Neutrino Sensitivity

Effectively comes for free in stereo UHECR mode

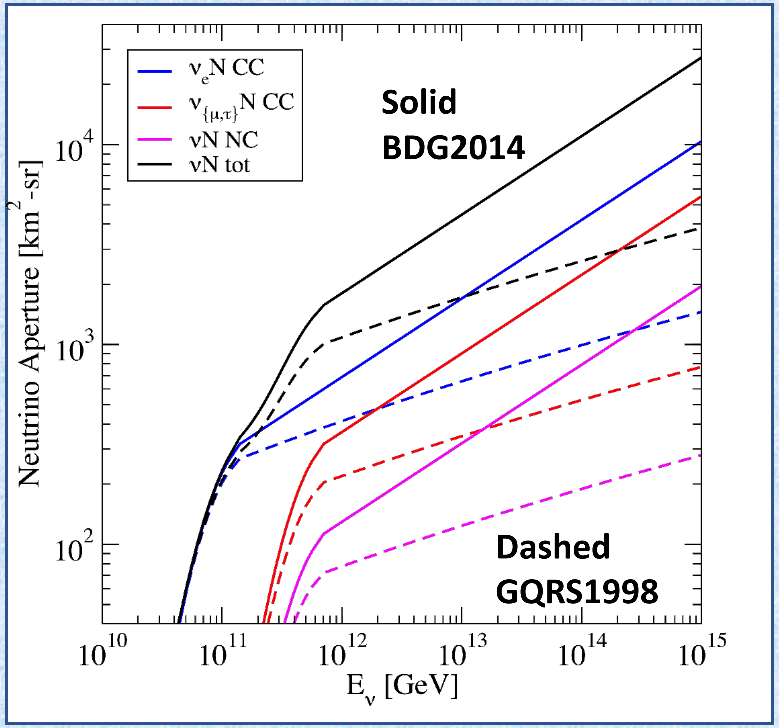
For $E_\nu \gtrsim$ 1 PeV, σ_{CC} & σ_{NC} virtually identical for ν & νbar

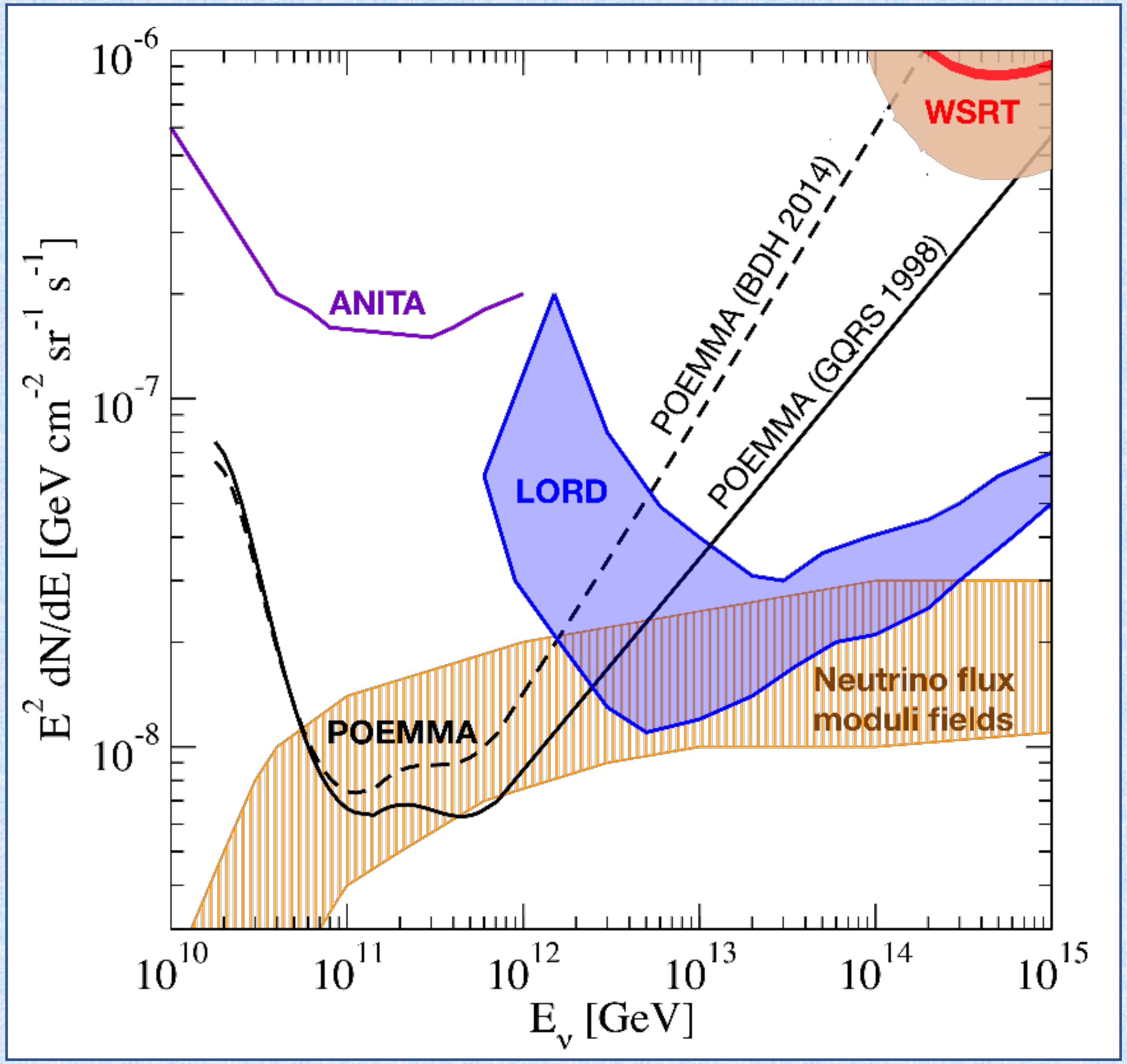
Assumptions:

- CC ν_e : 100% E_ν in EAS
- CC ν_μ & ν_τ : 20% E_ν in EAS ($\gamma c\tau_\tau \approx 5000$ km)
- NC ν_e & ν_μ & ν_τ : 20% E_ν in EAS

UHECR Background Probabilities (1 event in 5 years):

- Auger Spectrum (100% H): < 1%
- TA Spectrum (100% H): ≈ 4%



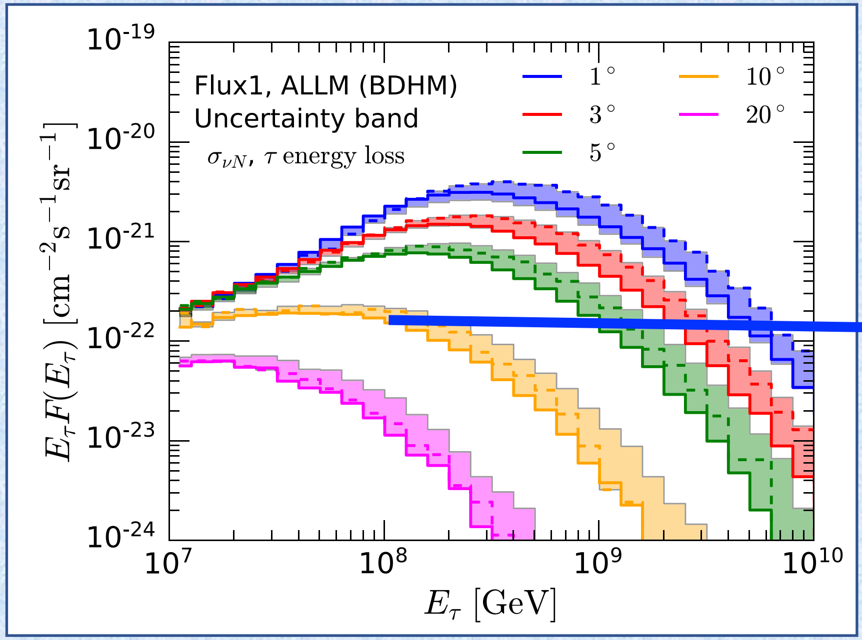


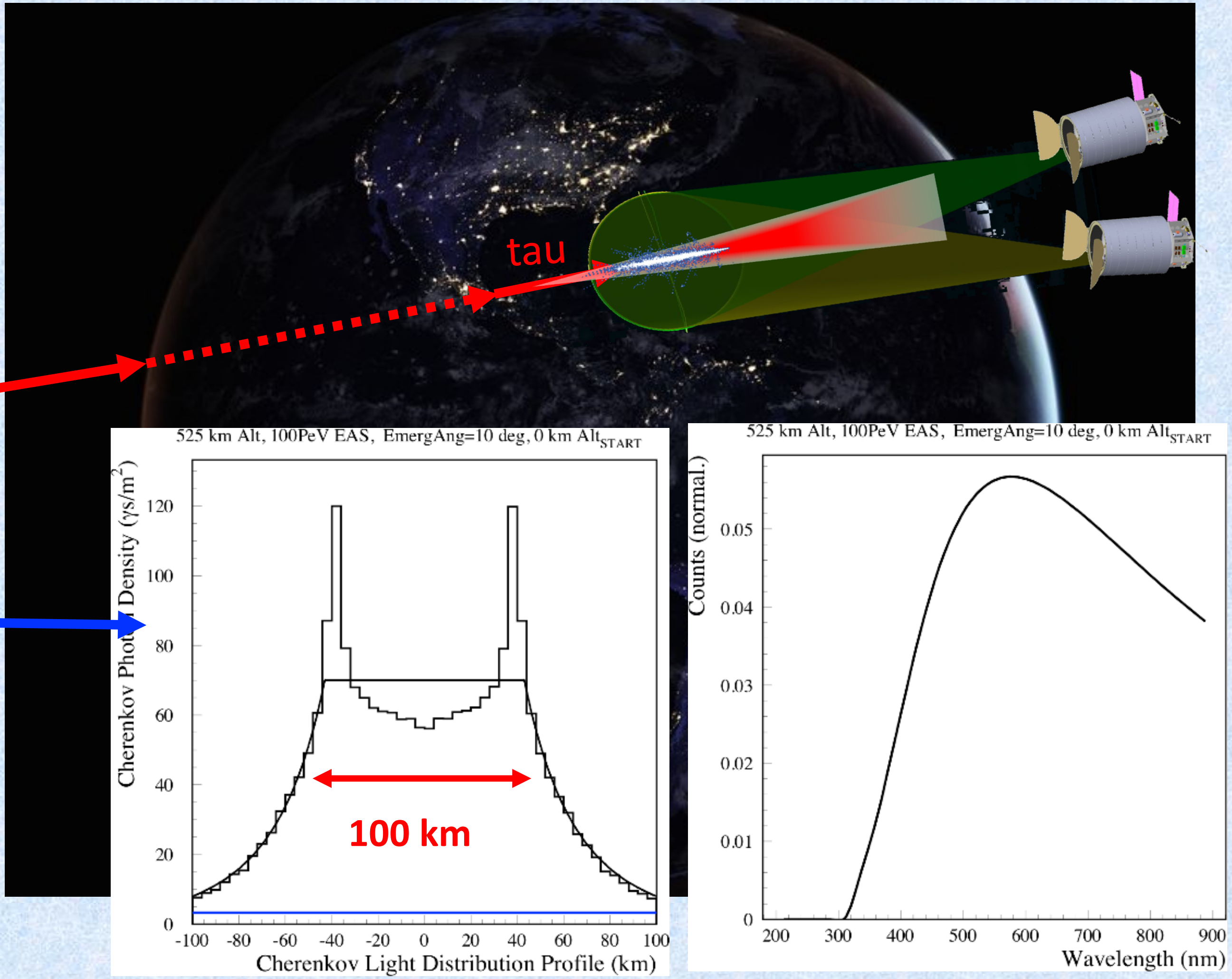
POEMMA Tau Neutrino Detection: *see PhysRevD.100.063010*

Reno, Krizmanic, & Venters

High-Energy Astrophysical Events generates neutrinos (ν_e,ν_μ) and 3 neutrino flavors reach Earth via neutrino oscillations: $\nu_e : \nu_\mu : \nu_\tau = 1{:}1{:}1$

POEMMA designed to observe neutrinos with E > 20 PeV through Cherenkov signal of EASs from Earth-emerging tau decays.





τ-lepton Yield Calc: PREM Earth Model: Kotera2010 mixed UHECR composition cosmogenic ν flux

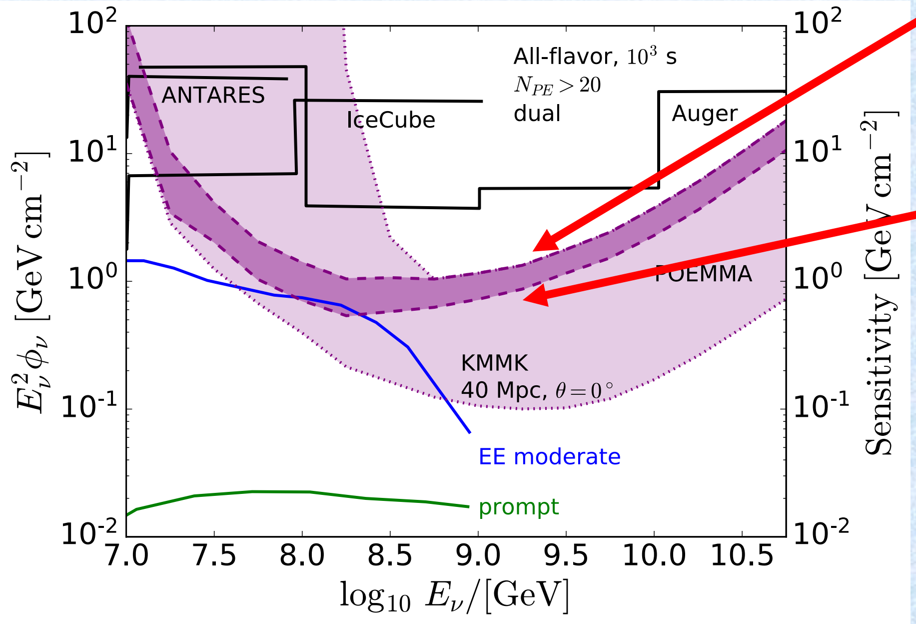
ToO Neutrino Sensitivity: *see arXiv:1906.07209*

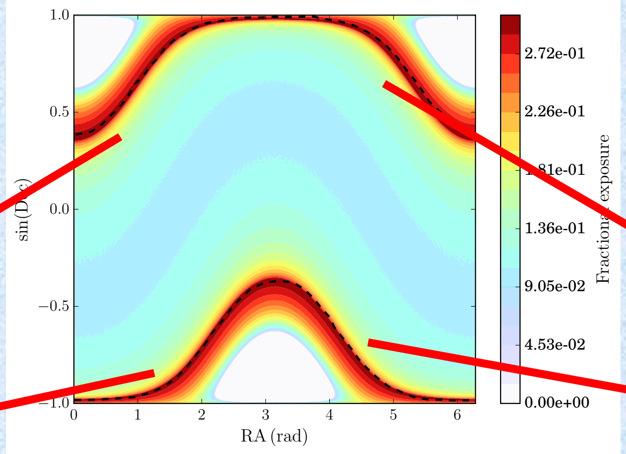
17% hit for ignoring $\tau \rightarrow \mu$ channel

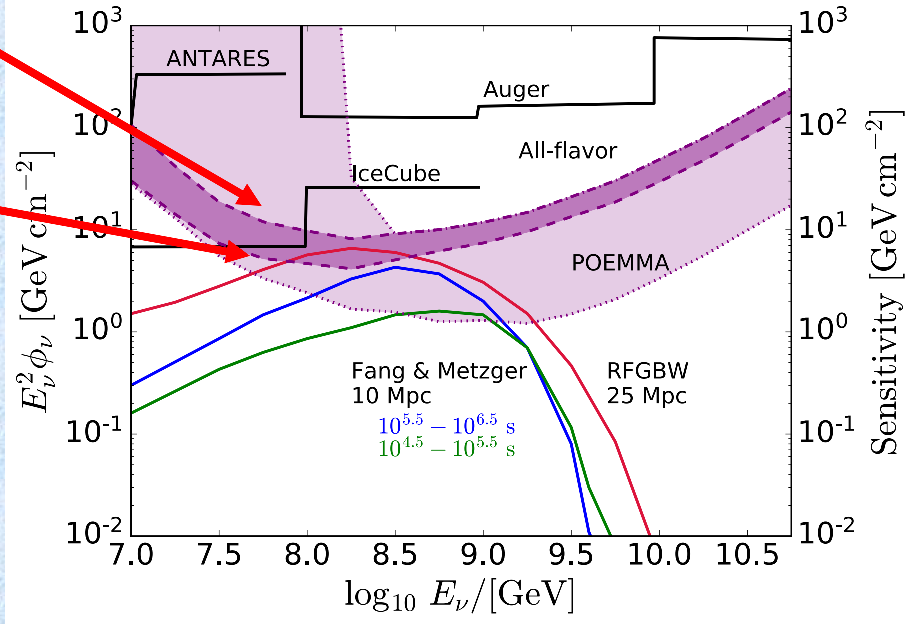
Short Bursts:
- 500 s to slew to source after alert
- 1000 s burst duration
- Source celestial location optimal
- Two independent Cher measurements
  - 300 km SatSep
- 20 PE threshold:
  - AirGlowBack < 10^{-3}/year

One orbit sky exposure assuming slewing to source position

Long Bursts:
- 1 day to set SatSep to 50 km
- Burst duration $\gtrsim 10^5$ s (models in plot)
- Average Sun and moon effects
- Simultaneous Cher measurements
  - 50 km SatSep
- 10 PE threshold (time coincidence):
  - AirGlowBack < 10^{-3}/year







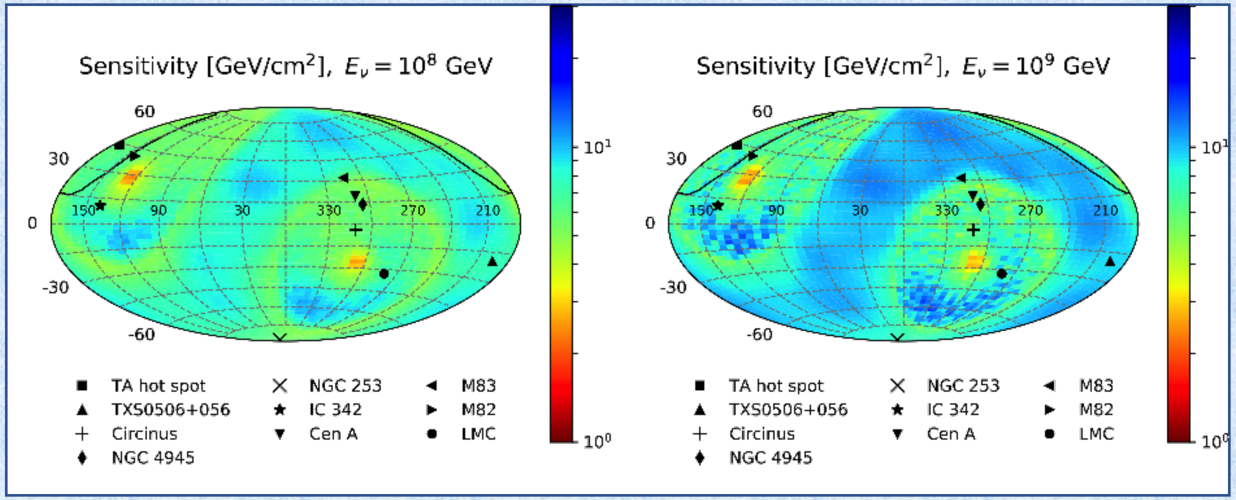
IceCube, ANTARES, Auger Limits for NS-NS merger GW170817

Summary

POEMMA will open two new Cosmic Windows:

- **UHECRS (> 20 EeV), to identify the source(s) of these extreme energy messengers**
  - All-sky coverage with significant increase in exposure
  - Stereo UHECR measurements of Spectrum, Composition, Anisotropy $E_{CR} \geq 50$ EeV
    - Remarkable energy (< 20%), angular ($\lesssim 1.2°$), and composition ($\sigma_{Xmax} \lesssim 30$ g/cm^2) resolutions
  - **Leads to high sensitivity to UHE neutrinos (> 20 EeV) via stereo air fluorescence measurements**
- **Neutrinos from astrophysical Transients (> 20 PeV)**
  - **Unique sensitivity to short- & long-lived transient events with 'full-sky' coverage**
  - **Highlights the low energy neutrino threshold nature of space-based optical Cherenkov method, even with duty cycle of order 10% – 20%**

***arXiv:1906.07209* Fig. 3**

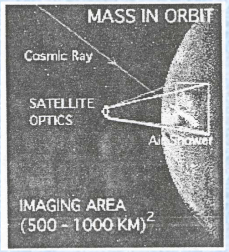


Work in Progress:

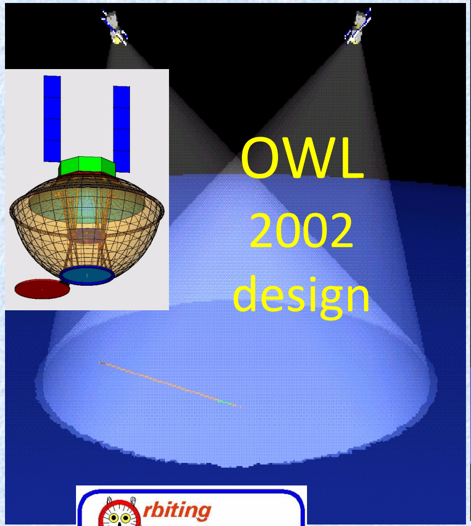
- **Neutrino Simulation work continue under funded NASA-APRA grant (3 year project):** Goal to develop *robust* end-to-end neutrino simulation package for space-based and sub-orbital experiment: ***optical Cherenkov and radio signals***
- **Modeling of τ–lepton → muon decay**
  - **Muons can have extended EAS to high altitudes, but muonic EAS have lower N_{part}**
  - **Austin Cummings (GSSI) working on this**

POEMMA: Heritage

Based on OWL 2002 study, JEM-EUSO, EUSO balloon experience, and CHANT proposal

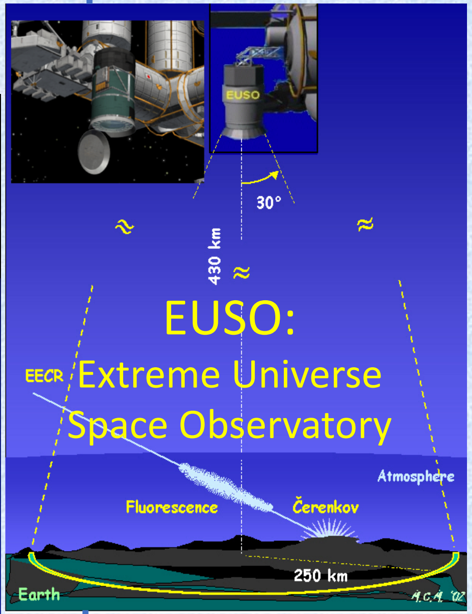


OWL
AIRWATCH



Orbiting
Wide-angle
Light-collectors

TUS, KLYPVE-EUSO



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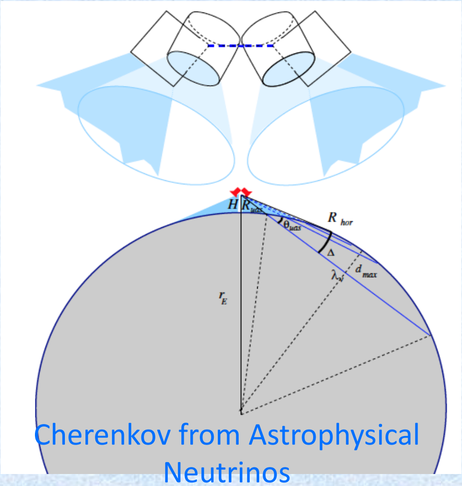


Cherenkov from Astrophysical
Neutrinos
Telescope

EUSO-Balloon
EUSO@TA
Mini-EUSO

EUSO-SPB2

Backup Slides

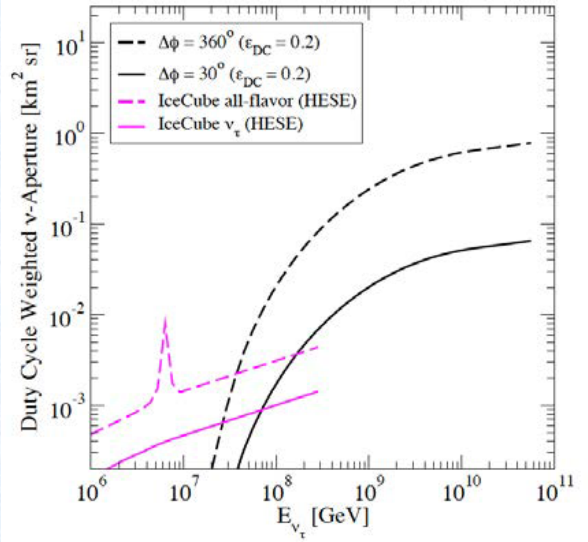
POEMMA: Diffuse neutrino flux sensitivity

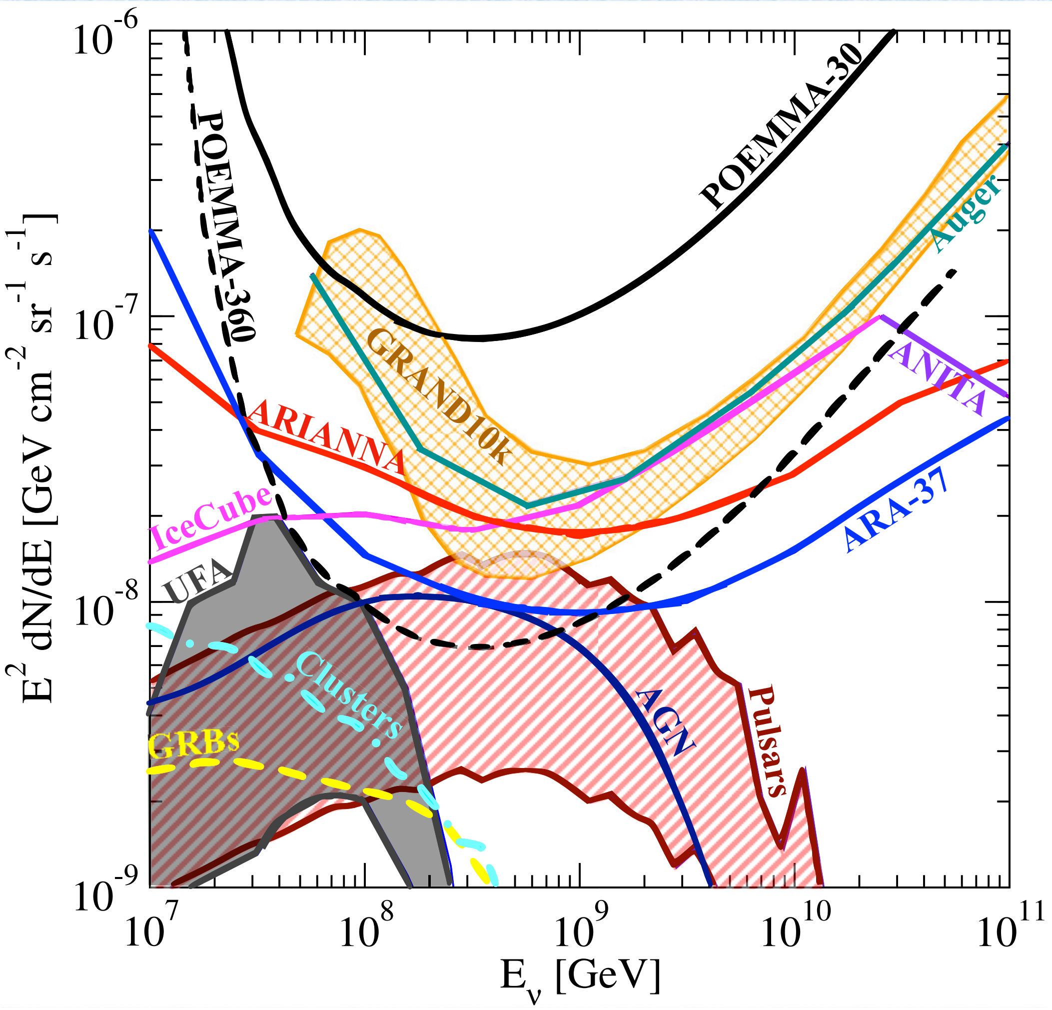
PhysRevD.100.063010 Fig. 22

All flavor Sensitivity Limit:

Air fluorescence UHE limits not included in plot

- 5 year
- 20% duty cycle
- 10 PE threshold with time coincidence to reduce air glow background 'false positives'
- 2.44 events/decade (90% CL)
- 17% hit for ignoring μ channel
- Viewing to 7° away from Limb (or to ~20° Earth Emerg Angle)
- $\nu_e : \nu_\mu : \nu_\tau = 1{:}1{:}1$





POEMMA ToO Performance: Comparison to Transient Models

Long Bursts				
Source Class	No. of ν's at GC	No. of ν's at 3 Mpc	Largest Distance for 1.0 ν per event	Model Reference
TDEs	1.12×10^5	0.77	2.64 Mpc	Dai and Fang [17] average
TDEs	5.62×10^5	3.88	5.91 Mpc	Dai and Fang [17] bright
TDEs	$\mathbf{2.23 \times 10^8}$	$\mathbf{1.44 \times 10^3}$	**115.20 Mpc**	**Lunardini and Winter [18] $M_{\rm SMBH} = 5 \times 10^6 M_\odot$ Lumi Scaling Case**
TDEs	**NA***	$\mathbf{1.07 \times 10^3}$	**100.03 Mpc**	**Lunardini and Winter [18] $M_{\rm SMBH} = 1 \times 10^5 M_\odot$ Strong Scaling Case**
Blazar Flares	**NA***	$\mathbf{1.91 \times 10^2}$	**42.96 Mpc**	**RFGBW [19] – FSRQ proton-dominated advective escape model**
lGRB Reverse Shock (ISM)	9.88×10^4	0.69	2.49 Mpc	Murase [15]
lGRB Reverse Shock (wind)	2.05×10^7	143.75	37.36 Mpc	Murase [15]
BH-BH merger	6.94×10^6	47.84	20.75 Mpc	Kotera and Silk [20] – $t_{\rm dur} \sim 10^4$ s
BH-BH merger	$\mathbf{3.48 \times 10^9}$	$\mathbf{2.4 \times 10^4}$	**477.8 Mpc**	**Kotera and Silk [20] – $t_{\rm dur} \sim 10^{6.7}$ s**
NS-NS merger	$\mathbf{3.58 \times 10^6}$	**24.75**	**12.76 Mpc**	**Fang and Metzger [21]**
WD-WD merger	20.06	0	33.46 kpc	XMMD [22]
Newly-born Crab-like pulsars (p)	1.56×10^2	1.07×10^{-3}	98.27 kpc	Fang [23]
Newly-born magnetars (p)	2.1×10^4	0.13	1.1 Mpc	Fang [23]
Newly-born magnetars (Fe)	4.07×10^4	0.26	1.53 Mpc	Fang [23]

Short Bursts				
Source Class	No. of ν's at GC	No. of ν's at 3 Mpc	Largest Distance for 1.0 ν per event	Model Reference
sGRB Extended Emission (moderate)	2.23×10^8	1.55×10^3	117.44 Mpc	KMMK [16]
sGRB Prompt	8.10×10^6	69.19	26.66 Mpc	KMMK [16]

(*) Not applicable due to mismatch with mass of SMBH at the GC and/or lack of blazar-like jet.

Bold: $\gtrsim$20% Prob of an event in 5 years

arXiv:1906.07209 version

Update in progress

POEMMA: anomalous ANITA upward EAS

arXiv:1803.05088v1

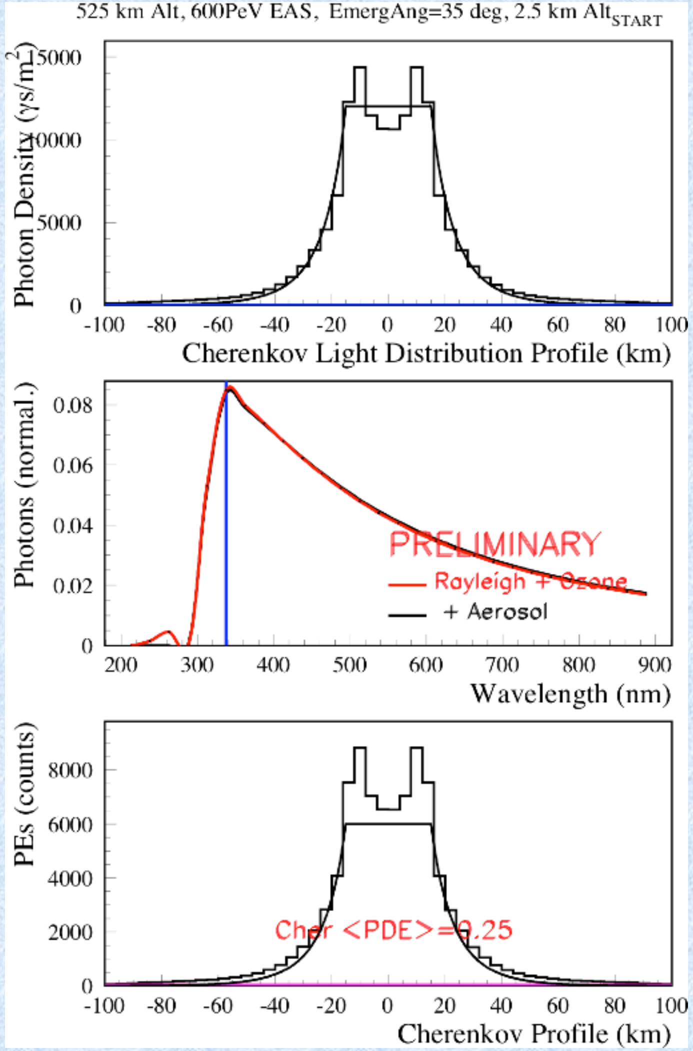
TABLE I: *ANITA-I,-III anomalous upward air showers.*

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.[1]	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3°, 159.62 \pm 0.7°$	$-35.0 \pm 0.3°, 61.41 \pm 0.7°$
RA, Dec[2]	282.14064, +20.33043	50.78203, +38.65498
E_{shower}[3]	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

[1] Latitude, Longitude of the estimated ground position of the event.
[2] Sky coordinates projected from event arrival angles at ANITA.
[3] For upward shower initiation at or near ice surface.

alt [km]	elevation [deg]	alpha [deg]	beta_e [deg]
34	-27.4	62.6	26.8
34	-35	55	34.6

POEMMA can tilt to view 9° × 30° 'spot'
But these events may be bright enough to be seen in the UV fluorescence detector with ~1 usec coincidence.



θ_{CONE}= 1.0 deg
$\omega \approx$ 1.e-3 sr

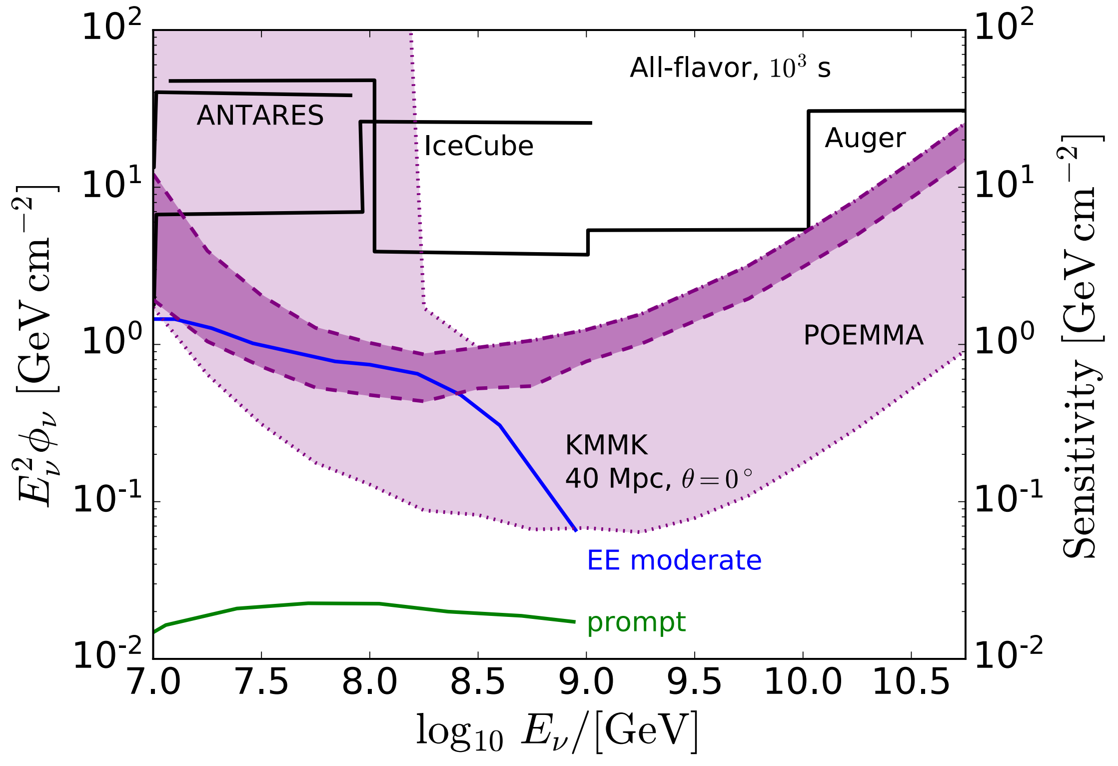
$\theta_{EFF} \approx$ 4.5 deg
$\omega \approx$ 2.e-2 sr

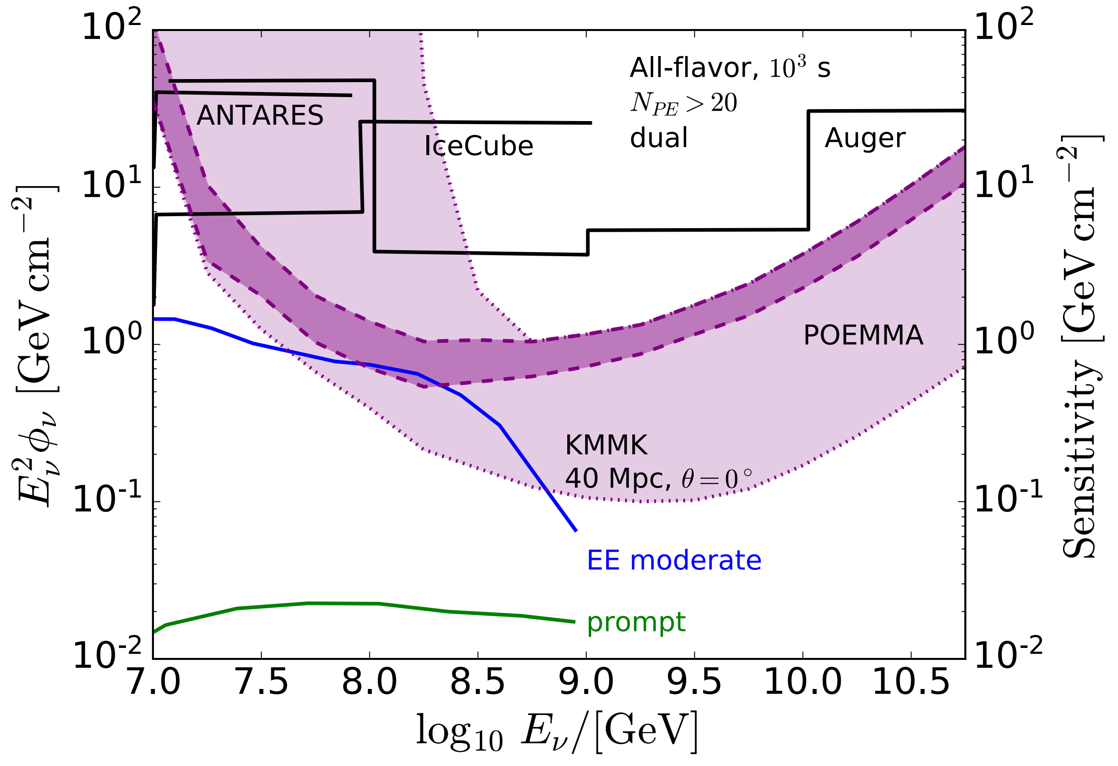
τ-lepton
$\gamma c \tau$ ~ 60 km
for 1.2 EeV

POEMMA signal size ~6000 PEs in cone

GF's similar (~200 km^2 sr): 2 events/70 days (ANITA 1-3) -> ~2 events per year for POEMMA

POEMMA Short Burst: 10 PE versus 20 PE comparison





10 PE threshold with simultaneous viewing of Cherenkov light pool and time coincidence (60 ns)

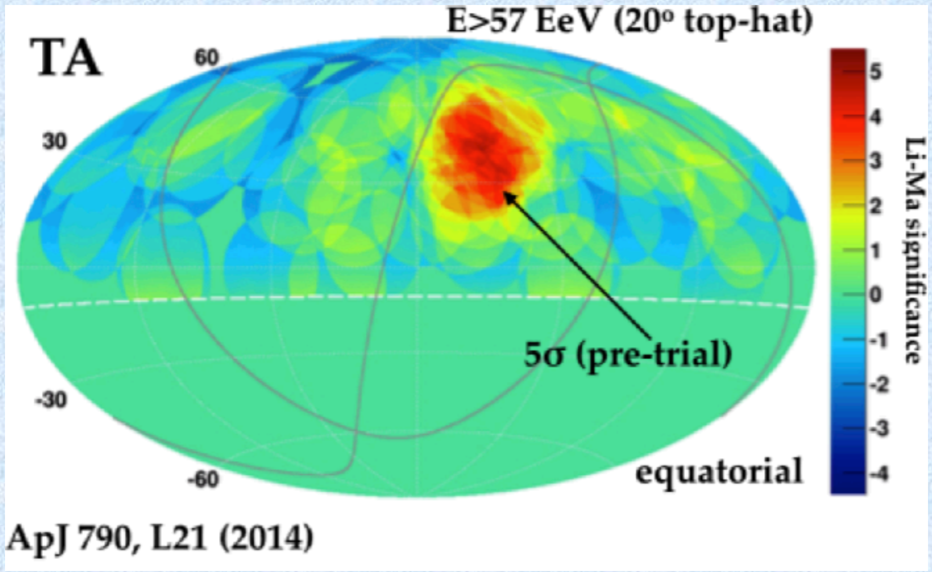
20 PE threshold with separate viewing of different Cherenkov light pool and times

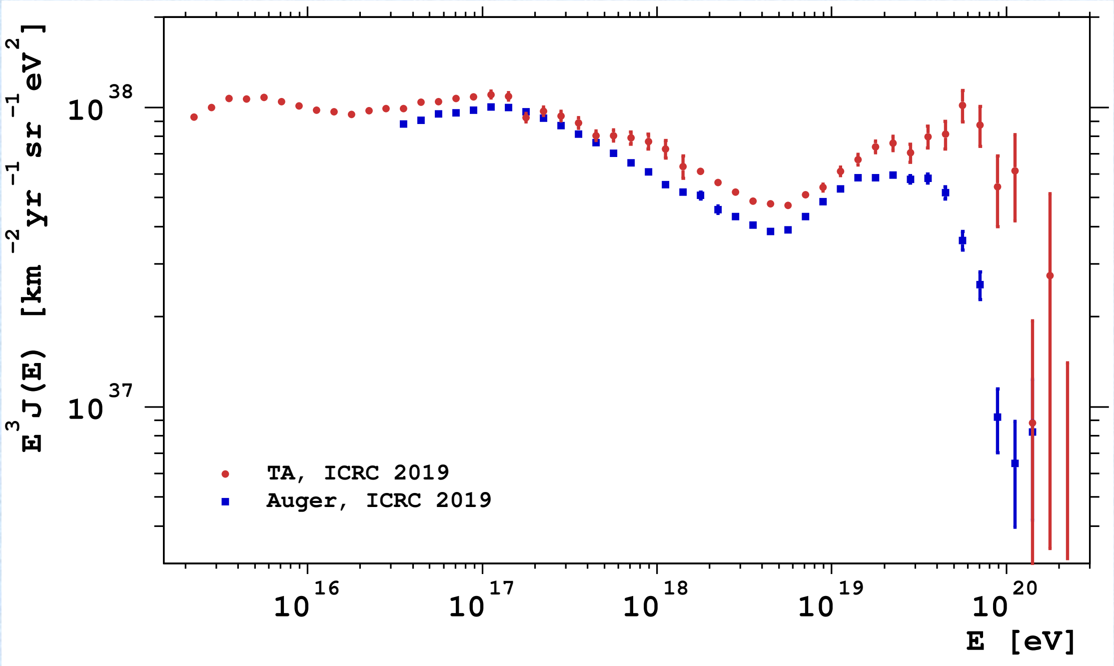
UHECR Status

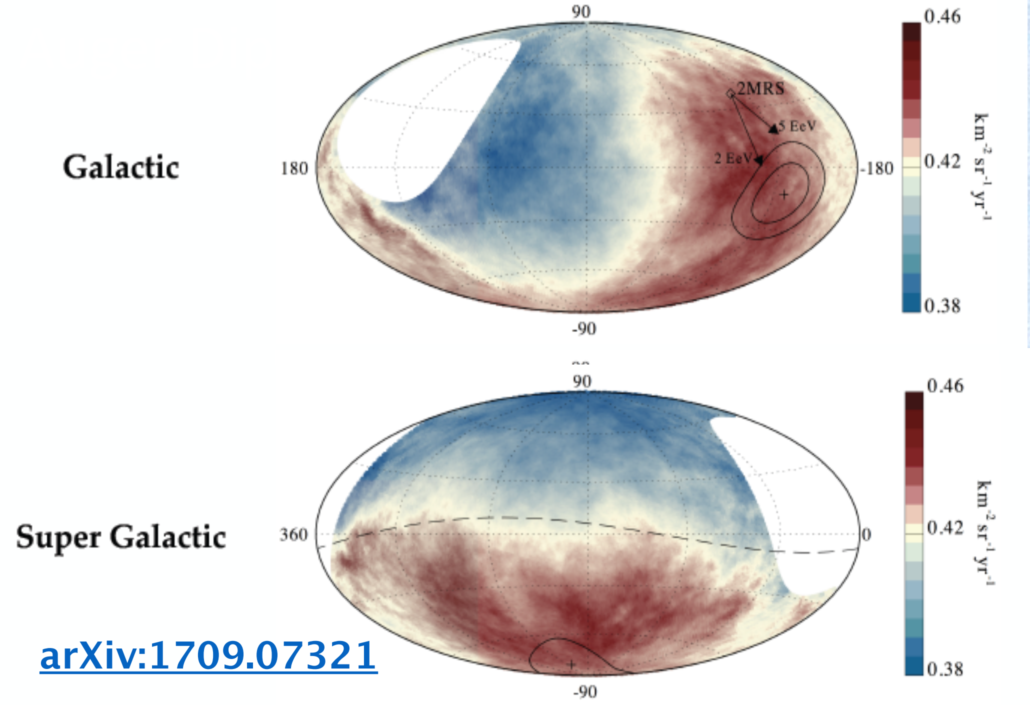
Origin UHECRs still unknown

Giant ground Observatories: Auger & TA

- sources are extragalactic: Auger dipole > 8 EeV
- spectral features – discrepancies E > 50 EeV
- interesting Composition trends – unknown E > 50 EeV
- source anisotropy Hints E > 50 EeV

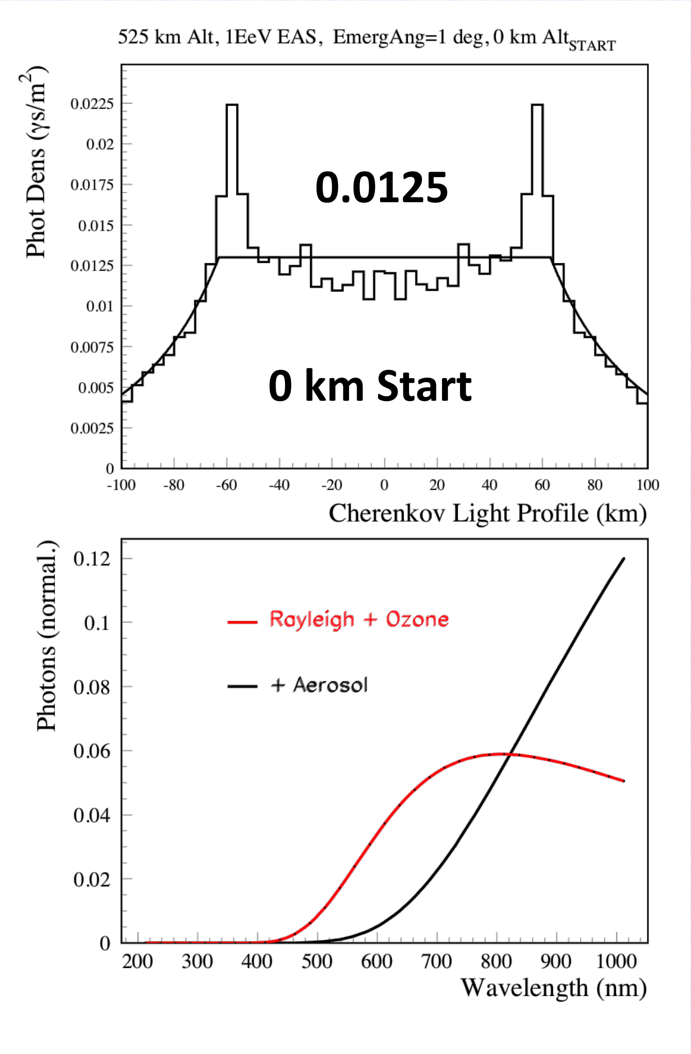






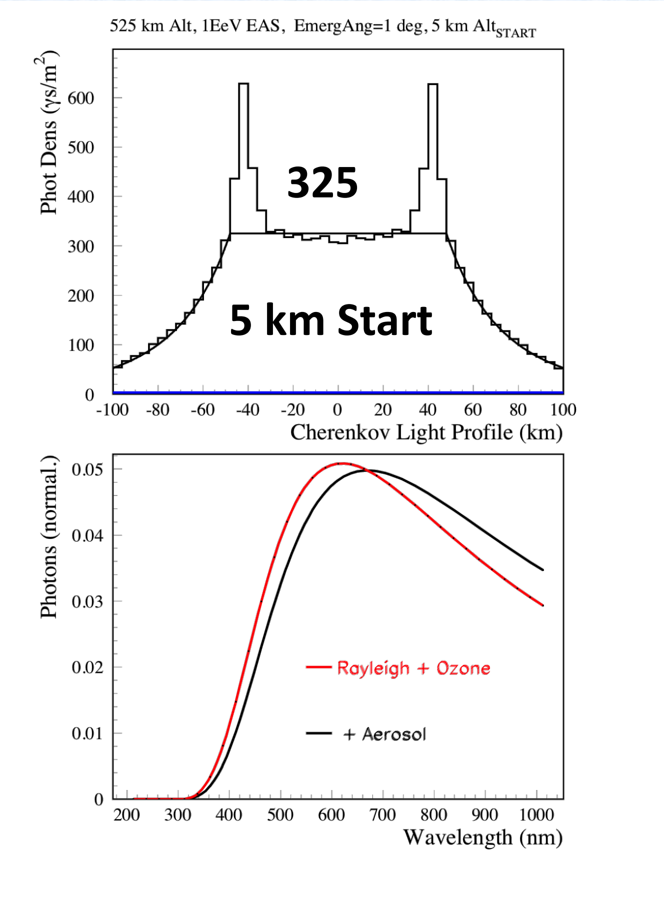
arXiv:1709.07321

POEMMA: upward τ-lepton EAS Cherenkov spectrum variability

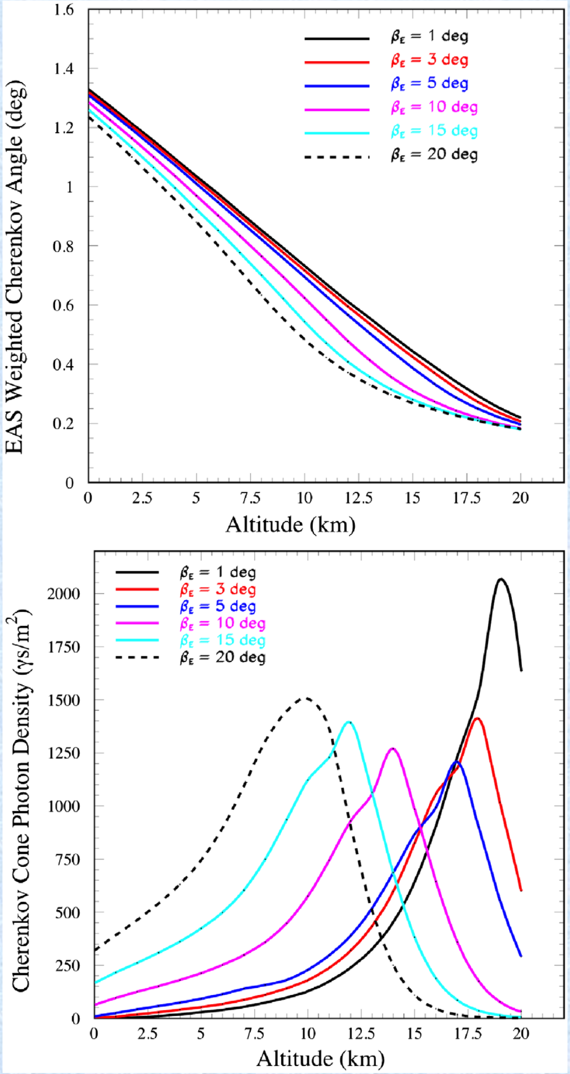


Atmospheric optical attenuation:

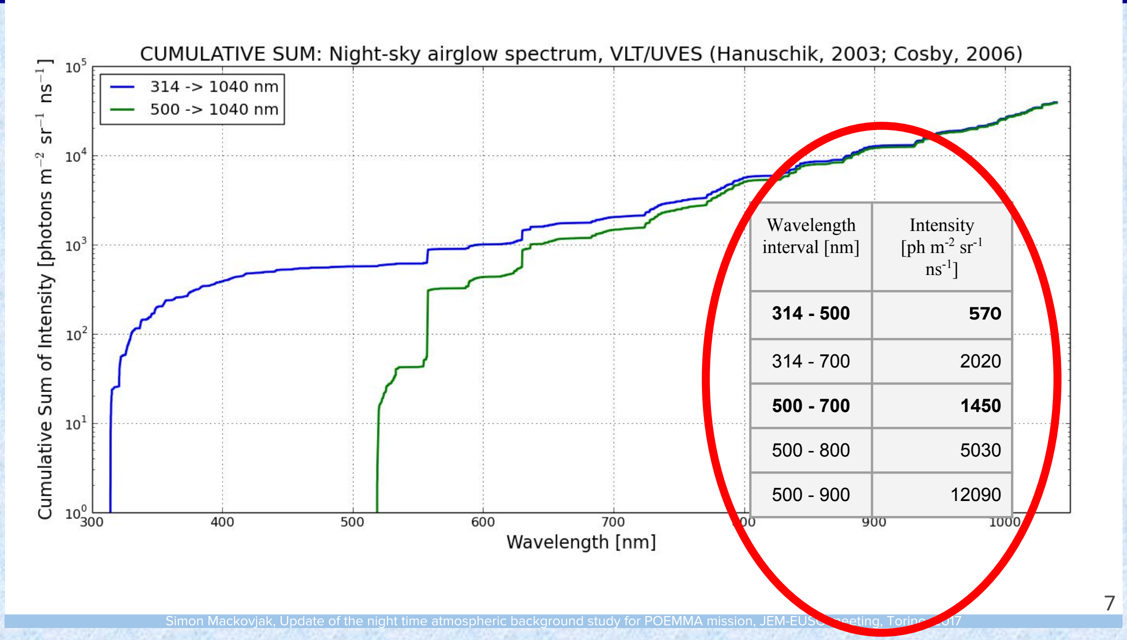
- **Rayleigh Scattering**
- **Aerosols (scale height ~ 1 km)**
- **Ozone (decimates signal $\lesssim$ 300 nm)**



PhysRevD.100.063010 Fig. 18



Air Glow Background in Cherenkov Band



314 nm – 900 nm

Use to calculate effective PDE (for SiPM): <PDE> = 0.1

12,090 photons/m²/sr/ns

314 nm – 1000 nm

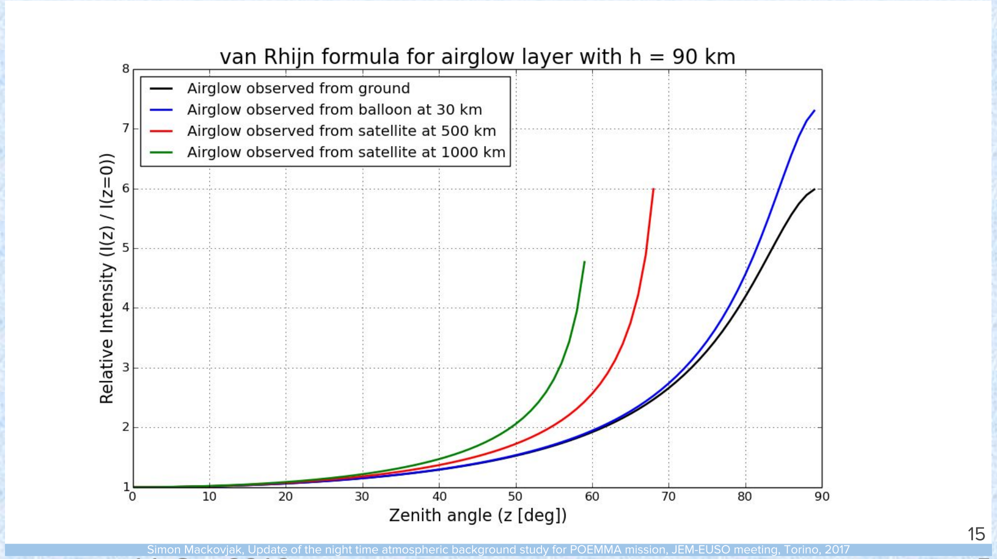
~25,000 photons/m²/sr/ns

314 nm – 500 nm

570 photons/m²/sr/ns

Requirement for < 1e-2 background events per year leads to high PE thresholds

- **10 PE (dual Cher measurement)**
- **20 PE (single Cher measurement)**

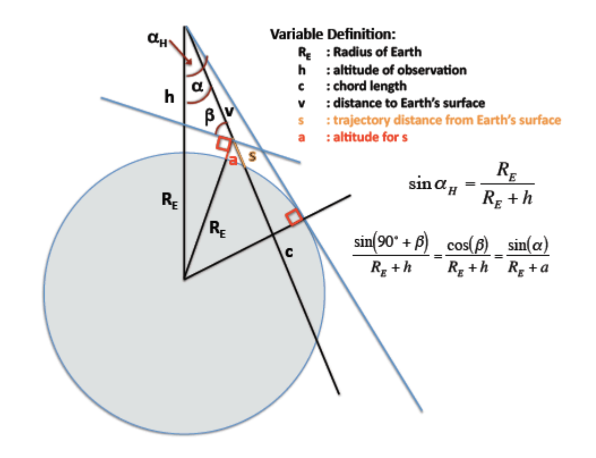


Viewing at angles away from nadir views more optical depth of air glow layer.

x6 for viewing limb from 500 km

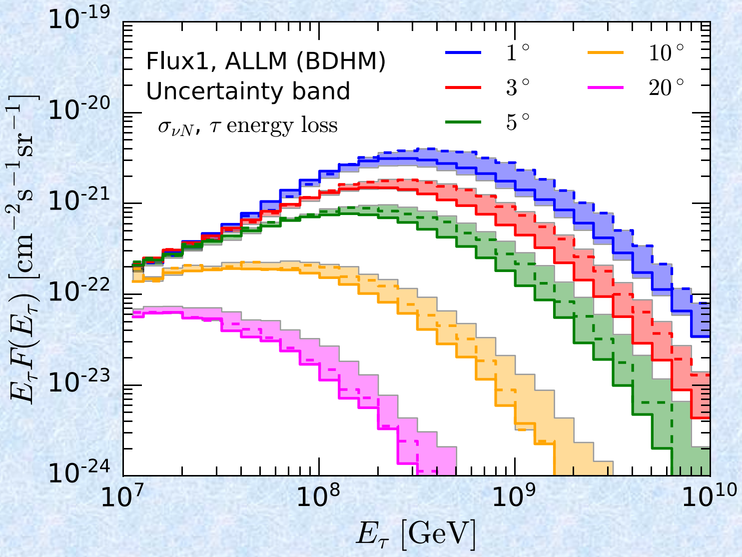
Work by Simon Mackovjak

POEMMA: upward τ-lepton EAS Cherenkov considerations

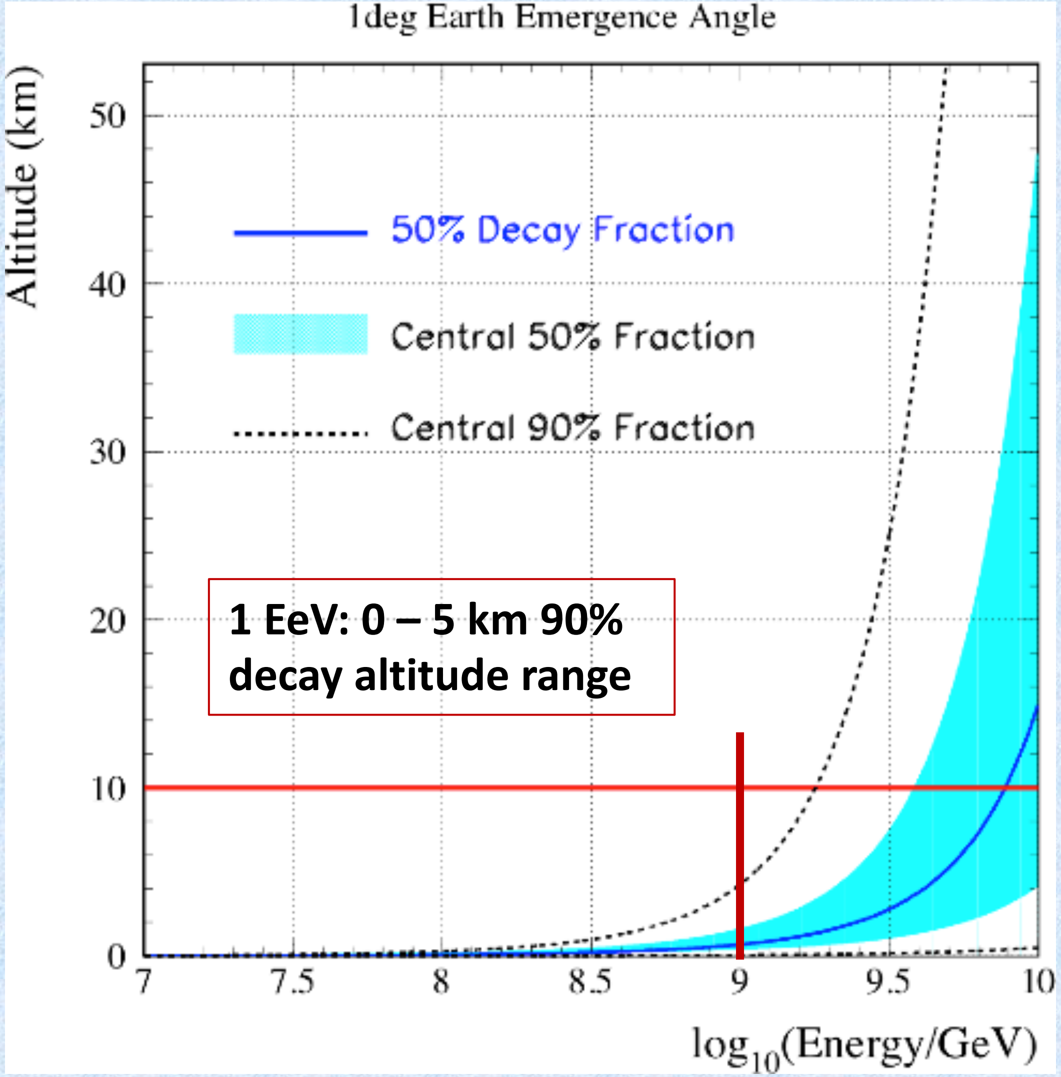


$\Delta\alpha$	β_E(33 km)	β_E(525 km)	β_E(1000 km)
1	3.6	7.0	8.2
2	5.2	10.0	11.7
3	6.6	12.3	14.5
4	7.9	14.4	16.9
5	9.1	16.2	19.0
6	10.3	18.0	21.0
7	11.4	19.6	22.8
8	12.6	21.2	24.6

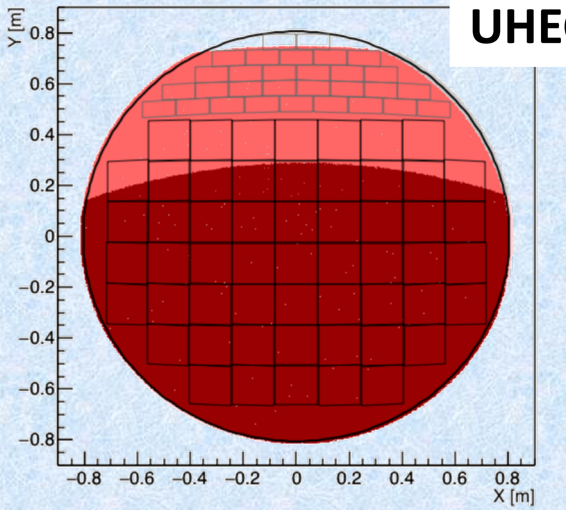
PhysRevD.100.063010 Fig. 12

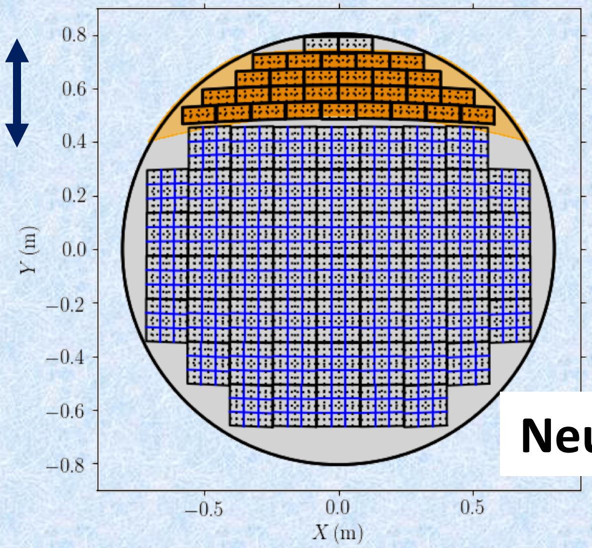


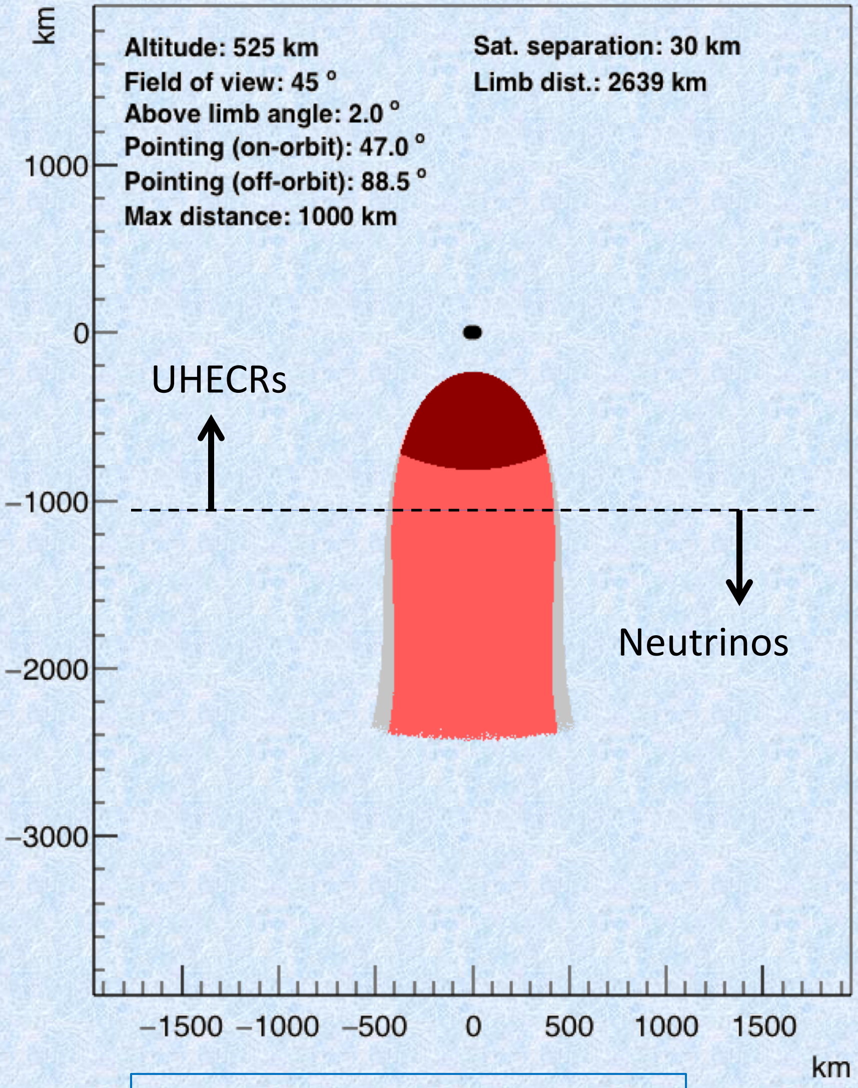
τ-lepton Yield Calc:
- **PREM Earth Model**
- **Kotera2010 mixed UHECR composition cosmogenic ν flux**



POEMMA: Neutrino mode example configuration







Calcs & plots by F. Sarazin